JUN 1927

VOLUME 29 SECOND SERIES NUMBER 6

Physics Lib.

THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED BY

THE AMERICAN PHYSICAL SOCIETY

BOARD OF EDITORS

Managing Editor: JOHN T. TATE, University of Minnesota, Minneapolis

K. K. DARROW, E. C. KEMBLE, F. L. MOHLER; J. A. GRAY, G. E. M. JAUNCEY, J. H. VAN VLECK; G. BREIT, P. W. BRIDGMAN, L. W. MCKEEHAN

JUNE, 1927

Theory of the Intensity of Scattered X-Rays — G. E. M. JAUNCEY 757
Effect of Chemical Combination on X-Ray Absorption — W. B. MORRHOUSE 765
Heat Energy of X-Rays — ROY KEGERREIS 775
On the Calculation of the Spectroscopic Terms Derived from Equivalent Electrons — HENRY NORRIS RUSSELL 782
Terms arising from Similar and Dissimilar Electrons — R. C. GIBBS, D. T. WILKER AND H. E. WHITE 790
Line Intensities in the Hydrogen Chloride Fundamental Band — D. G. BOURGIN 794
Relative Intensities of some Lines in the Mercury Spectrum — JOSEPH VALASEK 817
Probability of Ionization of Mercury Vapor by Electron Impact — T. J. JONES 828
Ionization by Collisions of the Second Kind in Mixtures of Hydrogen and Nitrogen with the Rare Gases — GAYLORD P. HARNWELL 830
Number of Radiating Atoms in a Hydrogen Discharge Tube — W. H. CREW AND E. O. HULBURT 843
Study of the Polarization of Light from Hydrogen Canal Rays — K. L. HERTEL 848
Electron Emission from Thoriated Tungsten — S. DUSHMAN AND JESSIE W. EWALD 857
Neutralization of the Deflecting Field in a Braun Tube with External Electrodes — L. T. JONES AND A. M. CRAVATH 871
Index of Refraction of Water for Short Continuous Waves — L. E. MCCARTY AND L. T. JONES 880
High Frequency Resistance of a Bureau of Standards Type Variable Air Condenser — S. L. BROWN, C. F. WIEBUSCH AND M. Y. COLBY 887
Note on the Plane Wave in a Gas — SATYENDRA RAY 892
Book Reviews 894

PROCEEDINGS OF THE AMERICAN PHYSICAL SOCIETY

Washington Meeting, April 22, 23, 1927; Minutes and Abstracts 1–94 901
Index to Volume 29 928

PUBLISHED BY THE AMERICAN PHYSICAL SOCIETY

MINNEAPOLIS, MINN.

THE AMERICAN PHYSICAL SOCIETY

OFFICERS OF THE SOCIETY

President:	K. T. Compton	Princeton University, Princeton, N.J.
Vice-President:	Henry G. Gale	University of Chicago, Chicago, Ill.
Secretary:	H. W. Webb	Columbia University, New York City.
Treasurer:	G. B. Pegram	Columbia University, New York City.
Editor:	John T. Tate	University of Minnesota, Minneapolis, Minn.
Local Secretary for the Pacific Coast:	D. L. Webster	Stanford University, Calif.

THE PHYSICAL REVIEW

Published monthly

Two volumes annually

First series. From July 1, 1893 to January 1, 1913, the Review was conducted by Edward L. Nichols, Ernest Merritt and Frederick Bedell, with the financial support of Cornell University. The first four volumes were issued annually; subsequent volumes, semi-annually; thirty-five volumes in all.

Second series. On January 1, 1913, the Review was transferred to the American Physical Society as announced on the first page of the new series which was then begun. Since then it has been conducted by a Board of Editors elected by the Society. Semi-annual volumes begin in January and July.

Contributors are referred to page 2 of the advertisements for further information.

Annual Subscription, throughout the Postal Union, $7.00 in advance.

Single Copies, $.75

General Index, 1893-1920, $4.00, in advance.

Back Volumes, $4.50 per volume; Back Numbers, $.75 per copy. Postage is free if remittance accompanies order; otherwise postage is extra. No bound volumes can be supplied. The Review offers to purchase a limited number of First Series, Vol. 1, No. 1 (at $1.50 each); Second Series, Vol. 7, No. 1, January 1916; Vol. 7, No. 2, February 1916; Vol. 7, No. 4, April 1916; and Vol. 7, No. 5, May 1916 (at $1.50 each).

Advertisements. Rates will be supplied by the Editor on request. Copy for each number must be received at Minneapolis before the 1st of the preceding month; old copy is used until new copy is received. Send electrotypes direct to the printers, George Banta Publishing Co., Menasha, Wisconsin.

Discount of ten percent is allowed subscription agencies and members of the American Physical Society.

Changes of address and Complaints of failure to receive the Review, in the case of members of the Physical Society, should be addressed to the Treasurer; otherwise, to the Editor. *New copies will be sent free only if complaint is received within three months of date of issue.*

Correspondence should be addressed to the Physical Review, 1500 University Ave. S. E., Minneapolis, Minn.

Entered at the postoffice at Menasha, Wis., as second class matter.
Acceptance for mailing at special rate of postage provided for in section 1103, Act of October 3, 1917, authorized September 6, 1926

Second Series *June, 1927* *Vol. 29, No. 6*

THE

PHYSICAL REVIEW

THEORY OF THE INTENSITY OF SCATTERED X-RAYS

By G. E. M. Jauncey

Abstract

The writer's theory of the unmodified line in the Compton Effect (Phys. Rev., **25,** 314, 1925) has recently been extended by Williams (Phil. Mag. 2, 657, 1926) and the writer (Phys. Rev., **29,** 206, 1927) to the case of reflection of x-rays by crystals. Both these writers assume that it is only the U electrons (i.e. the electrons associated with unmodified scattering, see Phys. Rev., **26,** 433, 1925) which take part in crystal reflection. In the present paper it is supposed that the U electrons in a given atom scatter coherently and also according to the classical theory, so that, if N_U is the number of U electrons in the atom, the intensity of the x-rays scattered in a given direction is N_U^2 times the intensity scattered by a single free electron in the same direction according to Thomson's theory. In previous papers it has been assumed that the intensity of unmodified scattering is proportional to N_U. Now, however, because of the above assumptions, it is proportional to N_U^2. In modified scattering it is assumed that the S electrons (i.e. the electrons associated with modified scattering)scatter incoherently and according tothe quantum theories of Compton, Jauncey and Breit. The modified scattering, as in previous papers, is,therefore,proportional toNS, the number of S electrons in the atom. Formulas are obtained for the energy of the total (i.e. unmodified plus modified) scattering coefficient and for the ratio of the modified to the total scattering coefficient in terms of the angle of scattering, the primary wave-length and the critical absorption wave-lengths of the scatterer. The theory seems to work equally well for heavy as for light elements and explains the phenomenon of excess scattering.

It is also pointed out that Williams has made a small error in his correction for the interference of x-rays scattered by the U electrons in atoms in the same crystal plane. Rectifying this error, an excellent agreement between theory and the experimental atomic structure factors as found by Havighurst (Phys. Rev., **28,** 869, 1926) for rock salt is obtained.

1. Introduction

According to Thomson's theory[1] of the scattering of x-rays, the linear scattering coefficient per unit solid angle in a direction ϕ with the primary rays is given by

$$s_0 = (NZ\rho/W) \cdot (e^4/m^2c^4) \cdot (1+\cos^2\phi)/2 \qquad (1)$$

where N is Avogadro's number, Z the atomic number of the scatterer, ρ its density, W its atomic weight and e, m and c the charge and mass of the electron and the velocity of light respectively. Eq. (1) agrees fairly well with

[1] J. J. Thomson, Conduction of Electricity through Gases, 2nd Ed., p. 325.

experiment for moderately soft x-rays scattered by light elements at angles greater than 60°. When gamma rays, however, are scattered the experimental value of the scattering coefficient, which we shall denote by s, is more nearly given by

$$s = s_0/(1+\alpha \text{ vers } \phi)^3 \tag{2}$$

as observed by Compton.[2] In Eq. (2) $\alpha = h/mc\lambda$, where λ is the wave-length of the primary x-rays. Eq. (2) has been derived on theoretical grounds by Compton, Jauncey and Breit.[3] However, for $\lambda = 0.545$A scattered by rock salt, Jauncey and May[4] have found for values of ϕ greater than 90° that s is between the value given by the right side of Eq. (2) and the Thomson value, s_0. For angles less than 90° s becomes greater than s_0, which phenomenon is known as excess scattering. This excess scattering was first observed by Crowther[5] and Barkla and Ayers[6] in the case of scattering by light elements. Later, Barkla and Dunlop[7] observed excess scattering when x-rays are scattered by heavy elements at 90°, while still more recently Jauncey and Coven[8] have observed this phenomenon for $\lambda = 0.41$A scattered by copper at 110°.

Jauncey's theory of the unmodified line in the Compton effect[9,10,11] supposes that unmodified scattering takes place from one set of electrons in an atom while modified scattering takes place from a second set of electrons. The electrons of the first set are said to be in the U state, while those in the second set are said to be in the S state For brevity we shall hereafter refer to the electrons associated with the unshifted and shifted lines as the U and S electrons. Jauncey's theory gives the ratio of the number of U electrons of a given type (K, L, M, etc.) to the total number of the same type when these electrons are moving in circular orbits as[12]

$$\frac{N_U}{N_U+N_S} \equiv y = 0.5 - \frac{\psi}{2(2T)^{1/2}} + \frac{V}{4\psi(2T)^{1/2}} \tag{3}$$

and

$$\psi = (h/mc\lambda)\sin\tfrac{1}{2}\phi, \tag{4}$$

where mc^2V is the ionization energy of each electron and mc^2T is the kinetic energy of each electron in its Bohr orbit. Since y has different values for

[2] A. H. Compton, Phil. Mag. **41**, 749 (1921) and Phys. Rev. **21**, 483 (1923).
[3] A. H. Compton, X-Rays and Electrons, p. 305.
[4] Jauncey and May, Phys. Rev. **23**, 128 (1924).
[5] J. A. Crowther, Proc. Camb. Phil. Soc. **16**, 112 (1910).
[6] Barkla and Ayers, Phil. Mag. **21**, 275 (1911).
[7] Barkla and Dunlop, Phil. Mag. **31**, 222 (1916).
[8] Jauncey and Coven, Phys. Rev. **28**, 426 (1926).
[9] G. E. M. Jauncey, Phys. Rev. **25**, 314 (1925).
[10] G. E. M. Jauncey, Phys. Rev. **25**, 723 (1925).
[11] Jauncey and DeFoe, Phys. Rev. **26**, 433 (1925).
[12] Eq. (3) is in the form given by Nuttall and Williams in Phil. Mag. **1**, 1217 (1926) Previously the writer has used a formula where $T = V$ which is approximately the case.

the different types (K, L, M, etc.) of electrons, the different y's are distinguished by the subscripts K, L, etc. If n_K, n_L, etc., are the numbers of K, L, etc., electrons per atom, then the average value of y, which we shall denote by $\bar{y}$, is

$$\bar{y}=\frac{n_K y_K+n_L y_L+\cdots}{n_K+n_L+\cdots} \tag{5}$$

Jauncey has also considered the case of scattering by electrons in elliptic orbits[10] and has obtained a more complicated formula than Eq. (3). The y's for elliptic orbits, such as the L_1 orbits, are supposed inserted in Eq. (5). If now it is assumed that the intensity of x-rays scattered in the direction ϕ by a U electron is the same as that scattered by an S electron, then Eq. (5) gives the ratio of the unmodified scattering coefficient s_1 to the total scattering coefficient (s_1+s_2), so that $s_2/(s_1+s_2)=1-\bar{y}$.

Woo[13] and DeFoe[14] have tested this point experimentally and find for x-rays of various wave-lengths scattered by various elements that the experimental value of $s_2/(s_1+s_2)$ is always considerably less than $(1-\bar{y})$. On the other hand Jauncey's theory of the unmodified line requires that when x-rays are passed through a gas in a Wilson cloud apparatus, the ratio of the number of recoil electron tracks to the number of photoelectron tracks should be $(1-\bar{y})\sigma/\tau$ where σ is the spherical scattering coefficient and τ the true absorption coefficient. Nuttall and Williams have found good experimental agreement with this prediction.

Summing up, we may say that the evidence is that Jauncey's theory of the unmodified line agrees well with experiment for those cases where the ratio of the numbers of U electrons to the number of the S electrons is concerned; while for those cases where the ratio of the intensities of the modified and unmodified rays is concerned the agreement is only qualitative and not quantitative. An attempt to explain this latter discrepancy and to rectify it is the purpose of this paper.

2. Intensity of X-rays Reflected by Crystals

The hint as to the explanation of this discrepancy appears in a recent paper by Williams.[15] Williams and independently, but later, the writer[16] have shown that it is necessary to take the Compton effect into account in order to explain the variation of the intensity of x-rays regularly reflected (not diffusely scattered) by crystals. Both Williams and Jauncey calculate the atomic structure factor F on the assumption that it is only the U electrons which take part in crystalline reflection. On this account therefore the effective number of electrons per atom in crystalline reflection is $\bar{y}Z$. However, as Compton,[17] Hartree[18] and others have shown, there is partial inter-

[13] Y. H. Woo, Phys. Rev. **27**, 119 (1926).
[14] O. K. DeFoe, Phys. Rev. **27**, 675 (1926).
[15] E. J. Williams, Phil. Mag. **2**, 657 (1926).
[16] G. E. M. Jauncey, Phys. Rev. **29**, 206 (1927).
[17] A. H. Compton, Phys. Rev. **9**, 29 (1917).
[18] D. R. Hartree, Phil. Mag. **50**, 289 (1925).

ference between the wavelets scattered (in crystalline reflection) from different electrons in the same atom. For instance Compton[17] has shown that if we consider only those electrons which are moving in circular orbits of radius a, the ratio of the average amplitude of the wavelet scattered by each electron in an atom to the amplitude of the wavelet scattered by a single free electron is

$$H=(\sin \xi)/\xi \tag{6}$$

where

$$\xi=(4\pi a \sin \tfrac{1}{2}\phi)/\lambda \tag{7}$$

Hartree[18] has also obtained a formula for the case where the electrons are moving in elliptic orbits and he gives tables of values of H for various values of ξ. Williams then obtains the atomic structure factor F thus:

$$F=n_K y_K H_K+n_L y_L H_L+ \cdots \tag{8}$$

the subscripts K, L, etc., referring to the K, L, etc., orbits. Eq. (8), however, is only justified if, when we consider circular orbits of a given radius, the U electrons can be in any position in the orbit and the orbit can be oriented in any direction. However, on reference to Jauncey's paper on the unmodified line,[10] it is seen that the U electrons are restricted to a certain area on the sphere of radius a. From Fig. 1 of this paper[10] it follows that the interference factor is only given by H when y is unity. As y approaches zero the interference factor approaches unity. Hence the writer has calculated the interference factor from the following approximate formula:

$$H'=1-y(1-H) \tag{9}$$

where H is given by Hartree's tables. This formula satisfies the conditions that $H'=1$ when $y=0$ and $H'=H$ when $y=1$. The formula for the structure factor F is therefore given by

$$F=n_K y_K H_K'+n_L y_L H_L'+ \cdots \tag{10}$$

Hartree[18] gives a formula for calculating the radius a of any circular orbit. From this value of the radius it is possible to calculate mc^2T, the kinetic energy of the electron in the orbit, by equating the moment of momentum to $kh/2\pi$ where k is the azimuthal quantum number. In this way values of T in Eq. (3) are calculated for circular orbits. For elliptic orbits T is calculated on the basis of a circular orbit of total quantum number equal to that of the elliptic orbit and then the method for calculating y for elliptic orbits according to a previous paper[19] is applied. However, these methods of calculating T are not applied to the outermost orbits. For these orbits it is considered best to take $T=V$ where V is given by the ionization potential.

Havighurst[20] has recently obtained experimental F values for rock salt from the intensities of different orders of reflection of Mo$K\alpha$ x-rays. Havighurst's values, however, contain the Debye temperature factor. Using the

[19] G. E. M. Jauncey, Phys. Rev. **27**, 687 (1926).
[20] R. J. Havighurst, Phys. Rev. **28**, 869 (1926).

temperature factor given by Bragg, Darwin and James[21] and inserting the wave-length used by Havighurst, values of F without the temperature effect have been obtained and are shown in the third column of Table I. The theoretical values as calculated from Eq. (10) are shown in the fourth column. The agreement between the third and fourth columns is good.

TABLE I

F-values for rock salt.

$\sin \frac{1}{2}\phi$	Experiment		Theory
	Including Temperature	Excluding Temperature	
0.126	20.80	21.6	19.0
0.252	11.60	13.5	12.0
0.378	6.69	9.46	8.2
0.504	3.54	6.30	6.7

In Eq (10) the distribution of electrons according to Stoner[22] is used, while the values of V in Eq. (3) are obtained from the National Research Council Bulletins written by Duane and by Compton and Mohler.

3. Intensity of X-Rays Scattered by Amorphous Substances

Since in crystalline reflection the U electrons in an atom scatter coherently, it is now assumed that the U electrons in an atom of an amorphous substance also scatter coherently. On the other hand an amorphous substance is distinguished from a crystal by the fact that the atoms of the amorphous substance scatter incoherently while the atoms of a crystal scatter coherently. Let p_ν be the probability that the number of U electrons in an atom is ν, where ν is a whole number. Assuming that the wavelets scattered by these U electrons are in phase, the amplitude scattered by each of these atoms is ν times the amplitude scattered by a single free electron so that the intensity scattered by each of these atoms is ν^2 times the intensity scattered by a free electron. Adding the intensities scattered by the atoms with 1, 2, $\cdots$, U electrons in the atom, the unmodified scattering coefficient s_1 is given by[23]

$$s_1 = s_0(1^2p_1 + 2^2p_2 + 3^2p_3 + \cdots + Z^2p_Z)/Z \qquad (12)$$

It is further assumed in this theory that the S electrons in an atom scatter incoherently so that for these electrons Z in Eq. (2) is replaced by the number

[21] Bragg, Darwin and James, Phil. Mag. **1**, 897 (1926).

[22] E. C. Stoner, Phil. Mag. **48**, 719 (1924).

[23] In crystalline reflection it is only necessary to know the average number of U electrons per atom since the amplitudes due to all the U electrons in the crystal are added. On this account the formula for the intensity of reflected x-rays (see Bragg, James and Darwin[21]) from an ideally imperfect crystal contains a factor N^2F^2 where N is the number of molecules per unit volume and F is the atomic structure factor. In other words the factor is $(NF)^2$ so that it is correct to take the average value of F. However, in scattering by amorphous substances, since we have assumed no coherence between the wavelets scattered by different atoms, the intensity contains a factor $N\overline{F}^2$, where $\overline{F}$ is the root mean square of the atomic structure factor and therefore in this case it is not correct to take the arithmetical average of F as is done in crystalline reflection. In a paper read by the author at the New York Meeting of the Physical Society in 1927 the author used the arithmetical average and therefore the formula given in the abstract of that paper is only approximately correct.

of S electrons per atom. Hence s_2 the modified scattering coefficient is given by

$$s_2=(1-\bar{y})s_0/(1+\alpha \text{ vers } \phi)^3, \tag{13}$$

where $\bar{y}$ is given by Eq. (5). From Eqs. (12) and (13), both (s_1+s_2) and $s_2/(s_1+s_2)$ can be obtained and compared with experiment.

The problem now reduces to finding an expression for p_ν in terms of the y's (as given by Eq. (3)) and also an expression for the summation, $1^2p_1+2^2p_2+\cdots$. Let us consider the case of a sack containing black and white balls such that the probability of drawing a white ball is y. Let us suppose that all the balls in the sack are emptied into baskets each of which contains, say, four balls. What are the probabilities that a basket will contain 1, 2, 3 or 4 white balls? The probability p_4 that a given basket will contain 4 white balls is y^4. Now let the probability of drawing a black ball out of the original sack be z so that $y+z=1$, then the probability of 1 black ball followed by 3 white balls being drawn is y^3z. However, in filling the baskets it matters not in what order the balls are drawn and, since all the drawings, *BWWW*, *WBWW*, *WWBW*, and *WWWB*, are equally likely, the chance p_3 of a basket containing 3 white balls and 1 black ball is $4y^3z$. It is easily seen that p_2, p_1 and p_0 are given by $6y^2z^2$, $4yz^3$, and z^4 respectively. The p's are therefore given by the terms in the expansion of the binomial $(y+z)^4$, the subscripts of the p's being equal to the exponents of the y's. It is easily seen that for baskets containing n balls each, the probabilities p_n, p_{n-1}, $\cdots$ are given by the respective terms of $(y+z)^n$. Next consider the case of two sacks, the probability of drawing a white ball from the first sack being y_1 and from the second sack y_2. Now let us take n_1 balls out of the first sack and n_2 out of the second sack and put the (n_1+n_2) balls in one basket. The probability p_ν that the basket will contain ν white balls is easily seen to be the sum of those terms in the expansion of $(y_1+z_1)^{n_1}\cdot(y_2+z_2)^{n_2}$ in which the sum of the exponents of the y's is ν. The argument can obviously be applied to any number of sacks.

Let us return to the case of one sack and baskets containing 4 balls and denote the summation $1^2p_1+2^2p_2+\cdots$ by S, then

$$S=4y(y+z)^2(4y+z) \tag{14}$$

But $y+z=1$ so that

$$S=4y(3y+1)=4y+4\cdot 3y^2 \tag{15}$$

The general formula for a basket containing n balls is

$$S=ny+n(n-1)y^2 \tag{16}$$

For the case of several sacks it can easily be shown that

$$\begin{aligned} S=&n_1y_1+n_2y_2+\cdots \\ &+n_1(n_1-1)y_1^2+n_2(n_2-1)y_2^2+\cdots \\ &+2n_1n_2y_1y_2+2n_1n_3y_1y_3+\cdots \end{aligned} \tag{17}$$

If we replace the subscripts 1, 2, 3, etc., by K, L, M and give the n's and y's the same meanings as in Eq. (5), the unmodified coefficient is then given by

$$s_1 = s_0 S/Z \tag{18}$$

4. Comparison with Experiment

Jauncey and Coven[8] have measured the total scattering coefficient (s_1+s_2) for $\lambda=0.41$A scattered by copper at various angles, their results being shown in the second column of Table II. In the third column are shown the theoretical values calculated according to Eqs. (12), (13) and (18). Stoner's distribution of $2K$, $2L_{\mathrm{I}}$, $6L_{\mathrm{III}}$, $2M_{\mathrm{I}}$, $6M_{\mathrm{III}}$, $10M_{\mathrm{V}}$ and $1N_{\mathrm{I}}$ electrons is used.

Table II

Scattering from copper: Wave-length 0.41A.

Scattering Angle, ϕ	Experiment $(s_1+s_2)/s_0$	Theory $(s_1+s_2)/s_0$
40°	4.8	4.00
50	3.5	3.11
60	2.5	2.55
70	2.37	2.25
80	2.14	1.90
90	1.49	1.62
100	1.45	1.47
110	1.52(?)	1.36
150		1.11
180		1.04

It is seen that there is fair agreement between the second and third columns. The experimental value at 110° is doubtful.

In Table III the experimental values of $s_2/(s_1+s_2)$ as determined by Woo[13] and DeFoe[14] are given in the third column, while the theoretical values are given in the fourth column.

Table III

Ratio of unmodified to total scattering.

Element, wave-length and experimenter	Angle	Experiment $s_2/(s_1+s_2)$	Theory $s_2/(s_1+s_2)$	$1-g$
Aluminum	90	0.48	0.62	.80
$\lambda=.71$A	105	.53	.67	.83
	120	.59	.73	.86
Woo.	135	.68	.79	.88
	150	.71	.81	.89
Copper	90	.55	.43	.82
$\lambda=.41$A	100	.63	.47	.84
	130	.84(?)	.55	.87
DeFoe				

The fifth column gives the ratio $s_2/(s_1+s_2)$ as calculated theoretically in a previous paper.[10] It is seen that the theory of the present paper gives values which approach closer to the experimental values than those calculated according to the method of the previous paper.

5. Discussion

A formula for the total scattering coefficient (s_1+s_2) has been obtained which agrees fairly well with the experimental results for copper (see Table II). The theory therefore seems to explain the phenomenon of excess scattering. However, the formulas for s_1 and s_2 as derived in Section 3 depend on the assumption that the wavelets scattered by the U electrons in an atom are in phase. Due to small differences of the paths of rays scattered by the various U electrons in the same atom this assumption is not quite true. A correction for partial interference should therefore be added. The interference factors calculated by Hartree[18] apply only to the case where the electrons are associated with crystal planes, and so cannot be used in the case of scattering by electrons in an amorphous substance. A correction might be made by using the methods of Debye[24] and Glocker and Kaupp[25] but this would complicate Eq. (12) by multiplying each term on the right side by an interference factor and so make impossible the derivation of the simple formula given in Eq. (18). The correction has therefore been omitted. The effect of the correction would be to diminish slightly the theoretical values in Table II and to increase slightly these values in Table III.

On the whole considering the evidence of Tables I, II, and III (DeFoe's values in Table III not being as reliable as Woo's values), it may be inferred that the experimental number of U electrons per atom is somewhat greater than that given by Eq. (5). From this it follows that the values calculated from Eq. (3) are somewhat too small. Since from Eq. (3) the conditions of wave-length and angle for which the unmodified line disappears[19] are given, it must be that the wave-length is smaller or the angle greater than the wave-length and angle given by Eq. (3) when the unmodified line disappears. An indication that this is so experimentally is given by the experiments of Woo[26] and Jauncey and Boyd.[27]

However, in spite of these small discrepancies, the writer believes that the theory as developed in this paper correlates surprisingly well the phenomena of the intensity of crystal reflection, the intensity of x-rays scattered by amorphous substances of high and low atomic numbers, the ratio of the energies of the modified and unmodified lines in the Compton Effect, and the conditions under which the unmodified line disappears.

Washington University,
St. Louis, Missouri,
February 14, 1927.

[24] P. Debye, Ann. d. Physik, **46,** 809 (1915).

[25] Glocker and Kaupp, Ann. d. Physik **64,** 541 (1921); see also Compton, X-rays and Electrons, p. 75.

[26] Y. H. Woo, Phys. Rev. **28,** 426 (1926).

[27] Jauncey and Boyd, Phys. Rev. **28,** 620 (1926).

EFFECT OF CHEMICAL COMBINATION ON X-RAY ABSORPTION

By W. B. Morehouse

Abstract

The x-ray absorption by aqueous solutions was measured before and after chemical reaction, employing a differential null method similar to that described by Becker (Phys. Rev. 20, 134, 1922). The direct and zirconium filtered beam from a water-cooled molybdenum Coolidge tube, operating at 30 kv peak, were used. Cells having equal compartments were used, so that the same elements were in the beam before and after combination.

Measurements were made on the following reactions:

(A) $KI+I_2+2Na_2S_2O_3 \rightarrow KI+2NaI+Na_2S_4O_6$.

(B) $K_2Cr_2O_7+12KI+14HCl \rightarrow 8KCl+2CrCl_3+3I_2+6KI+7H_2O$

(C) $NaOH+HCl \rightarrow NaCl+H_2O$.

(D) $KOH+HCl \rightarrow KCl+H_2O$.

(E) I_2 in 70 percent alcohol $+2Na_2S_2O_3 \rightarrow 2NaI+Na_2S_4O_6$.

Corrections having been made for changes in density the results indicate: Reaction (A); the mass absorption coefficient for the solution after reaction for direct beam approximately 0.24 percent less than before reaction; for filtered beam 0.36 percent less: Reaction (B); direct beam; 0.25 percent greater: Reaction (C); direct beam; no appreciable change: Reaction (D); direct and filtered; no appreciable change: Reaction (E); direct beam; 0.36 percent less. The results indicate that the mass absorption coefficient for an element depends upon its valence or state of chemical combination. Since iodine, sulphur and chromium are the only elements changing valence and since computations from known absorption coefficients show that the absorption by the iodine in the beam is several times that by either the sulphur or the chromium, its seems probable that the absorption by iodine in the free state is greater than its absorption in the combined state.

Introduction

Benoist,[1] from the result of his measurements on x-ray absorption, first stated that the x-ray absorption coefficient for an element is the same whether the element is in the free state or combined chemically with other elements. In fact one finds the same statement made in various books on x-rays.[2]

Several investigators[3] have measured the x-ray absorption by chemical compounds and, assuming the above law, have computed the absorption coefficients of the elements present in the compounds. A critical comparison of the results obtained by these experimenters, as pointed out by Taylor[3], indicates that the absorption coefficient for an element may depend upon

[1] Benoist, Journal de physique; **10,** 658, (1901).

[2] W. H. and W. L. Bragg, X-rays and Crystal Structure, 4th ed., p. 41. de Broglie, Les Rayons X, 1922 ed., p. 48. Kaye; X-rays, 4th ed., p. 125. Ledoux, Lebard et Danvillier, La Physique des Rayons X, p. 135.

[3] Auren, Phil. Mag. **33,** 471 (1917); Phil. Mag. **37,** 135, (1919); Phil. Mag. **41,** 733, (1921); Taylor, Phys. Rev. **20,** 709, (1922).

its state of chemical combination with other elements. Further, Bergengren,[4] Lindh,[5] and other investigators[6] recently have shown that for the light elements the wave-length of the absorption limits and of certain emission lines does depend upon the valence of the element. Absorption coefficients for any wave-length must certainly be closely related to emission spectra and absorption limits. Accordingly this investigation was undertaken to study the effect of valence or chemical combination on x-ray absorption.

The absorption by two solutions placed in an x-ray beam was measured. They were then allowed to react chemically and the change in absorption after reaction was measured. Corrections were, of course, made for changes in density. An effect due to chemical combination has been found and measured but no quantitative claim is made for the present results. Further experiments should be performed to determine the value of the effect for different wave-lengths.

Experimental Procedure

For measuring the relative absorption before and after chemical reaction a differential null method[7] was employed. By means of two slit systems

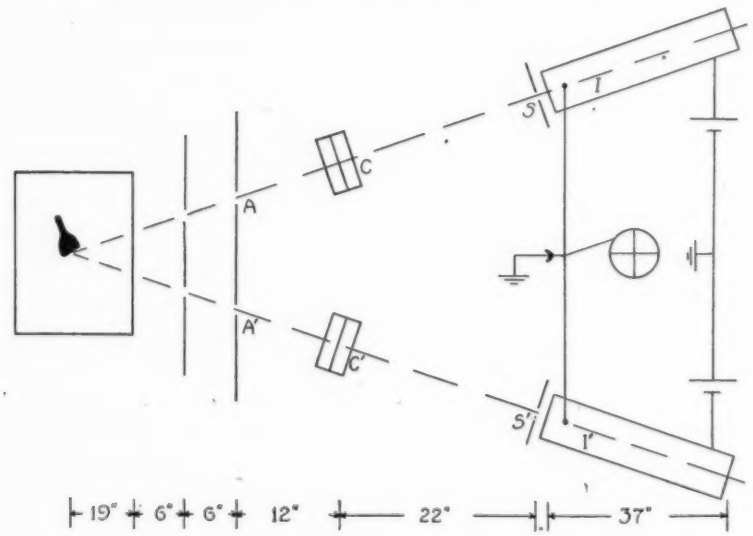


Fig. 1. Diagram of apparatus.

two x-ray beams A and A' from a molybdenum target of a water-cooled Coolidge tube were made to enter two ionization chambers I and I' respectively. These beams if unabsorbed would pass directly through the

[4] Bergengren, C. R. **171,** 624 (1920).

[5] Lindh, C. R.; **172,** 1175 (1921); Fysisk, Tidskr.; **20,** 132 (1922); C. R.; **175,** 25 (1922); Arkiv. f. Matem. Astr. o. Fys.; **18,** 12 (1924).

[6] Tandberg, Arkiv. f. Matem., Astr. o. Fys. **18,** 1 (1924). Chamberlain, Phys. Rev.; **25,** 525 (1925).

[7] Becker, Phys. Rev. **20,** 134 (1922). Read, Phys. Rev. **27,** 373 (1926).

chambers without hitting their walls or the central rods. The projected area of the beam on the back end of ionization chamber I' was approximately 1.5 sq. in. (10 cm^2) at a distance of approximately 9 feet (2.75 m.) from the target. Methyl bromide was placed in the chambers to increase the absorption of the x-rays. The chambers were connected together by rubber tubing so the pressures would equalize. The outside of one chamber was charged positive and the other equally negative. In front of chamber I' was a fixed slit S' 1 in. (2.54 cm) square and in front of chamber I an adjustable slit S easily adjustable to one forty thousandth of an inch. The insulated central rods in the ionization chambers were connected together and to a Compton electrometer. A balance was readily obtained when the electrometer showed no rate of drift. The apparatus was very sensitive and a change in balance of one part in ten thousand, measured in terms of the adjustable slit, could readily be detected.

Equal volumes of the solutions before reaction were placed in a cell C' having two equal compartments separated by either a removable or a fixed partition. In the case of the removable partition the solutions were allowed to react chemically by removing the partition and replacing it after the reaction was completed. In the case of the fixed partition the solutions were poured together into a beaker and after complete reaction the mixture was replaced in the cell. This cell C' was placed in the path of beam A'. Another cell C containing similar solutions was placed in the path of beam A to reduce to a minimum the relative changes in intensity of the two beams due to slight unavoidable fluctuations in the operation of the x-ray tube.

The exact procedure in getting the measurements was as follows. The empty cell C' was placed in beam A'. Then the cell C' plus solutions was placed in beam A'. Next the similar cell C and solutions were placed in beam A. Finally the solutions in beam A' were allowed to react. For each case the slit opening S_0, S, S_1 and S_2 necessary for a balance was obtained.

The cells employed were made from bakelite. Each compartment was 3/8 in. (1 cm) wide. The sides and partition were of bakelite 1/16 in. (1.6 mm) thick. Other cells were used which had the sides and partition of aluminum 0.020 in. (0.5 mm) thick covered with bakelite lacquer, and of hard rubber 1/16 in. thick. Measurements with any cell gave the same results.

The change in balance caused by the reaction may be due to either a change in the absorption coefficient of the solutions or to a change in density or both. Therefore it was necessary that the densities of the solutions before and after reaction be known accurately. For this purpose a Westphal balance was used.

The positions of the solutions relative to the direction of the beam were interchanged to be sure that the effect was not due to scattering caused by the different positions of the elements before and after reaction. This would also eliminate any error due to the compartments not being equal.

A source of alternating current for operating the x-ray tube was obtained by running a rotary converter from a Terrill regulated D. C. generator. Four 100 ampere-hour 6 volt storage batteries were soldered together giving a 12 volt source for the filament. Sufficient time was always allowed for the batteries to approach a constant discharge rate, after which the tube electron current decreased very steadily and at a very slow rate. In all cases the voltage across the tube was 30 K.V. peak.

Measurements were taken using the unfiltered direct beam from the tube. Later an approximately monochromatic beam was obtained by filtering the direct beam through zirconium filters.

All records and computations were made in terms of the adjustable slit width and the density of the solutions before and after reaction.

Formulas

It can readily be shown that for a simple homogeneous mechanical mixture of several elements which are absorbing monochromatic x-rays.

$$\mu=\frac{\mu_a\rho_a+\mu_b\rho_b+\mu_c\rho_c+\cdots}{\rho_a+\rho_b+\cdots+\rho_m+\rho_n+\cdots} \tag{1}$$

where μ is the mass absorption coefficient of the mixture, μ_a, μ_b, etc., are the mass absorption coefficients and ρ_a, ρ_b, etc., are the partial densities in gm per cc for each element present in the mixture. The density of the mixture is equal to the sum of the partial densities. Also it can be shown that for solutions not too concentrated the energy absorbed by a given thickness of the solution is directly proportional to the density.

In the present experiment the rate at which energy I enters the chambers is directly proportional to the slit opening S. (over at least a small range of openings.) i.e.

$$I=KS \tag{2}$$

When no substances are in beam A, if S_0 is the slit opening necessary to effect a balance with the box only in beam A', and S the slit opening with the box plus solutions in the same beam then

$$S=S_0e^{-[\mu_1\rho_1x_1+\mu_2\rho_2x_2]} \tag{3}$$

where μ_1 and μ_2 are the mass absorption coefficients given by Eq. (1), ρ_1 and ρ_2 the density, x_1 and x_2 the thickness of solutions (1) and (2) respectively.

Assuming (1) that the solutions are at the same level in each compartment and (2) that there is no change in either the density or the absorption coefficient it can readily be shown that the transmission after reaction will be the same as before and

$$S=S_0e^{-\mu\rho' x} \tag{4}$$

where μ is given by Eq. (1), $\rho'=(\rho_1+\rho_2)/2$, and $x=x_1+x_2$.

In general a change in density due to the reaction will occur and also there may be a change in μ. This will necessarily cause a change in the

transmission and from Eq. (4) a relation between the change in transmission as measured by the change in slit opening, the change in μ, and the change in density can readily be obtained by differentiating and dividing, remembering that x and S_0 are constant.

$$\frac{dS}{S \cdot 2.303 \log_{10} S/S_0} = \frac{d\mu}{\mu} + \frac{d\rho}{\rho'} \tag{5}$$

dS is the change in slit opening necessary to regain a balance after reaction. $d\rho$ is equal to the difference between the measured density ρ after reaction and ρ'.

The only effect of a change in temperature due to the reaction will be to produce a change in density for Read[8] has shown that the effect of temperature on the absorption coefficient is less than one percent for changes in temperature of 500°C.

The following will show that when a heterogeneous x-ray beam of definite intensity passes through several different materials the amount of energy absorbed is independent of the order in which the materials are placed and if they are mixed it is independent of the order in which the molecules are arranged. The amount of energy absorbed will, however, depend upon the ratio of the intensities of the various wave-lengths present in the beam.

Consider an x-ray beam, composed of two wave-lengths λ_1 and λ_2 of energy $I_{0\lambda_1}$ and $I_{0\lambda_2}$ respectively, which passes through two substances A and B. Let a_1 and a_2, b_1 and b_2 be the absorption constants for substances A and B corresponding to wave-lengths λ_1 and λ_2 respectively. Let I_1 and I_2 be the energy corresponding to wave-lengths λ_1 and λ_2 which gets through the substances. Then

$$I_1 = I_{0\lambda_1}(1-a_1)(1-b_1) \tag{6}$$

$$I_2 = I_{0\lambda_2}(1-a_2)(1-b_2) \tag{7}$$

and the energy of the emerging beam is given by

$$I_1 + I_2 = I_{0\lambda_1}(1-a_1)(1-b_1) + I_{0\lambda_2}(1-a_2)(1-b_2) \tag{8}$$

Equations (6) and (7) are independent of the order in which the beam encounters the molecules of the substances and therefore the energy transmitted which is given by Eq. (8) must be independent of the order in which the beam encounters the molecules of the substances.

The energy absorbed by the substances is given by

$$\begin{aligned}(I_{0\lambda_1} + I_{0\lambda_2}) - (I_1 + I_2) &= (I_{0\lambda_1} + I_{0\lambda_2}) - [I_{0\lambda_1}(1-a_1)(1-b_1) + I_{0\lambda_2}(1-a_2)(1-b_2)] \\ &= I_{0\lambda_1}(a_1 + b_1 - a_1 b_1) + I_{0\lambda_2}(a_2 + b_2 - a_2 b_2)\end{aligned} \tag{9}$$

The average absorption constant for the substances is given by

$$\overline{X} = \frac{(I_{0\lambda_1} + I_{0\lambda_2}) - (I_1 + I_2)}{I_{0\lambda_1} + I_{0\lambda_2}} \tag{10}$$

[8] Read, Phys. Rev. **27**, 373, 1926.

Therefore

$$\overline{X}=\frac{I_{0\lambda_1}(a_1+b_1-a_1b_1)+I_{0\lambda_2}(a_2+b_2-a_2b_2)}{I_{0\lambda_1}+I_{0\lambda_2}} \tag{11}$$

Equation (11) shows that the average absorption constant $\overline{X}$ depends on the ratio of the energy in each wave-length to the total energy in the beam and is only constant provided these ratios are constant. This argument may be extended to include any number of wave-lengths and any number of substances.

Therefore the absorption of heterogeneous x-rays by materials depends upon the energy in the various wave-lengths to the total energy in the beam, and therefore will depend upon the x-ray tube, the voltage applied to the tube, and upon the manner in which the x-rays are filtered.

For a constant ratio between the energy in the various wave-lengths of the x-ray beam the change in the mass absorption coefficient of the solutions due to the chemical reaction can be computed from Eq. (5).

Solutions Studied and Experimental Results

The following reactions were studied using dilute solutions,

$$[KI+I_2]+(2Na_2S_2O_3)\rightarrow KI+2NaI+Na_2S_4O_6. \tag{A}$$

12.7 grams of iodine were dissolved in 1000 cc of a solution of potassium iodide which contained 25 grams of KI per liter. The solution of sodium thiosulphate contained 25 grams $Na_2S_2O_3\cdot 5H_2O$ per liter. Equal volumes reacted.

$$[K_2Cr_2O_7+6KI]+(6KI+14HCl)\rightarrow 8KCl+2CrCl_3+3I_2+6KI+7H_2O. \tag{B}$$

The solution of potassium dichromate contained 5 grams $K_2Cr_2O_7$ per liter. The solution of potassium iodide contained approximately 40 grams KI per liter and the solution of HCl contained 10 grams HCl per liter. The reaction was the equivalent of equal volumes of these solutions reacting.

$$[NaOH]+(HCl)\rightarrow NaCl+H_2O. \tag{C}$$

The solution of sodium hydroxide contained 28 gms NaOH per liter. The solution of HCl contained 26 gms HCl per liter. Equal volumes reacted.

$$[KOH]+(HCl)\rightarrow KCl+H_2O \tag{D}$$

The solution of potassium hydroxide contained 28 grams KOH per liter and the solution of HCl contained 18 grams HCl per liter. Equal volumes reacted.

$$[I_2 \text{ in } 70\% \text{ alcohol}]+(2Na_2S_2O_3)\rightarrow 2NaI+Na_2S_4O_6. \tag{E}$$

12.7 grams of iodine was dissolved in 70% solution of alcohol making a liter of solution. The solution of sodium thiosulphate contained 25 grams of $Na_2S_2O_3\cdot 5H_2O$ per liter. Equal volumes were used.

In each case the substances in square brackets were initially in one compartment of the cell and the substances in round brackets in the other compartment.

Sample of Calculations

The following is a complete sample set of data and computations on Reaction A.

Voltage across tube: 30 kv peak.
X-ray tube electron current: 10.4 milliamperes.
Sensitivity of electrometer: 2000 mm per volt.
Volume of each solution used: 160 cc.

S_0:	1.2494″	1.2495″	1.2500″	Average	1.2496
S:	0.1720	0.1717	0.1717		0.1718
S_1:	0.9881	0.9883	0.9885	0.9882	0.9883
S_2:	0.9950	0.9953	0.9953	0.9954	0.9952

S_1 is the slit opening with similar solutions in both beam A and B before reaction and S_2 is the slit opening after the solutions in beam A have reacted.

Density of $[I_2+KI]=\rho_1=1.0266$ gm per cc.
Density of $(Na_2S_2O_3)=\rho_2=1.0124$ gm per cc.
Density of solution after reaction $=\rho=1.0182$ gm per cc.

$$\rho'=(\rho_1+\rho_2)/2=1.0195 \text{ gm per cc.}$$
$$d\rho=\rho'-\rho=-0.0013 \text{ gm per cc.}$$
$$dS=S_1-S_2=-0.0069''.$$
$$\frac{dS}{2.303\ S_1 \log_{10}(S/S_0)}=\frac{d\mu}{\mu}+\frac{d\rho}{\rho'}$$
$$d\mu/\mu=-0.0022.$$
$$\text{Change in } \mu=-0.22\%.$$

Table I

Values of the change in absorption coefficient resulting from chemical reaction. The last line in the table gives the average percent change in μ for each type of reaction studied. In case 1 the x-ray beam passed through the substance in square brackets first, and in case 2 it passed through the substances in round brackets first.

Reaction A Unfiltered beams (percent)		Reaction A Zirconium filtered beams (percent)		Reaction B Unfiltered beams (percent)		Reaction C Unfiltered beams (percent)		Reaction D Unfiltered beams (percent)		Reaction D Zirconium filtered beams (percent)		Reaction E Unfiltered beams (percent)	
1	2	1	2	1	2	1	2	1	2	1	2	1	2
−.36	−.17	−.22	−.33	+.27	+.15	+ 21	−.13	−.06	+ 19	−.02	+.09	−.40	−.23
−.29	−.23	−.18	−.19	.45	20	.18	−.00	−.05	.00	+.09	.09	− 35	−.31
−.30	−.42	−.64	−.41	.31	.32	.18	−.09	−.16	.04	−.18	.20	−.36	−.23
−.35	−.22	−.33	−.18	.21	.21	.14	−.05	−.09	.05	−.06	.13	−.31	−.23
−.22	−.31	−.59	−.27	.20	.22	.12	−.18	−.13	.07	+.05	−.06	− 36	−.29
−.21	−.40	−.25	−.23	.18	.21	.11	−.20	−.17	.01	−.10	+.15	−.28	−.34
−.10	−.15	−.44	−.24	.48	.35	.12	−.12					−.24	−.38
−.27	−.21	−.43	−.76	.33	.31							−.35	−.54
−.08	−.20		−.35	.32	.31							−.53	−.54
−.23	−.16			.22	.25							−.54	−.50
	−.14			.21	.25								
				.12	23								
				.12	.16								
				.17	.17								
−.24	−.24	−.33	−.38	+.26	+.24	+.15	−.11	−.11	+.06	− 04	+.10	−.37	−.34
±.03	±.03	±.04	±.04	±.03	±.02	±.02	±.02	±.02	±.02	±.03	±.03	±.02	±.03
−(.24 ± .03)		−(.36 ± .04)		+(.25 ± .03)		+(.02 ± .02)		−(.03 ± .02)		+(.03 ± .03)		−(.36 ± .03)	

In reaction (A) and (E) the iodine changes its valence from 0 to -1 and the valence of the sulphur increases positively. In reaction (B) the iodine changes its valence from -1 to 0 and chromium from 6 to 3. In reaction (A) the amount of iodine per sq. cm in the beam before and after reaction was .032 gms of which .013 gms changed its valence. In reaction (B) the amount of iodine per sq. cm in the beam before and after reaction was .031 gms of which .013 gms changed its valence. In reaction (E) the amount of iodine per sq. cm in the beam before and after reaction was .013 gms and all of it changed its valence.

In reactions (C) and (D) the valence of all elements in the beam is the same after reaction as before. For these determinations a cell with a removable partition was used and the compartments were not exactly equal. Equal volumes were used and the solutions were not at the same level which explains why the effect is positive for one case and negative for the other. The average of the results being practically zero (at least within experimental error) indicates that probably the effect due to the reaction is approximately zero.

The results in general indicate that the mass absorption coefficient for an element depends upon its valence and is therefore different for different states of chemical combination. Computations from known absorption coefficients show that the absorption by the iodine in the beam was several times (approximately 15 times) that due to either the sulphur or the chromium, which indicates that probably the measured effect is practically all due to the iodine. This is also indicated by the results for reaction (E) where all the iodine changed its valence.

The larger effect from reaction (A) when using the filtered beam may indicate that the effect is different for different wave-lengths of x-rays, or it may be caused by the change in the ratio of the intensities of the various wave-lengths present in the beam as indicated by Eq. (11). The filtered x-rays when using a zirconium filter are at best only approximately monochromatic.

Theoretical Explanation of Results and a Comparison with the Results of Experiments Indicating a Dependence of the Wave-Length of Absorption Limits and Emission Spectra Upon Valence.

Experimental results[9] show that on the short wave-length side of the K absorption limit the atomic absorption coefficient can be represented by the following approximate formula

$$T_a = CN^4\lambda^3 . \tag{1}$$

where T_a is the atomic absorption coefficient; C is a constant; N is the atomic number; and λ is the wave length of the x-rays. On the long wave-length side of the limit the formula has practically the same form excepting the exponents may be slightly different, and C is different.

[9] Richtmyer, Phys. Rev. **17**, 264 (1921); Richtmyer & Warburton, Phys. Rev. **21**, 721 (1923).

For the K absorption limit, Moseley's law may be written in the form

$$\lambda_K = K_1/(N-b)^2 \tag{2}$$

where λ_k is the wave length of the absorption limit, K_1 is a constant, N is the atomic number, and b is the screening constant.

If Eq. (2) be combined with Eq. (1) there results[10]

$$T_a' = C'N^4/(N-b)^6 \tag{L}$$

where T_a' is the atomic absorption coefficient just at the short wave-length side of the absorption limit.

Differentiating Eq. (3) with respect to T_a' and b there results

$$dT_a'/T_a' = 6db/(N-b) \tag{4}$$

which at once indicates that if the screening constant increases the value of T_a' increases, and vice versa.

The results of several experimenters[4,5,6] show that in general the absorption limit comes at a shorter wave length when the element is in the combined state than when it is in the free state, also that the wave length is different when the element is combined under different valences. Usually the higher the valence the shorter the wave length. On the basis of Moseley's law, equation (2), this must mean that the value of the screening constant, when the element is in the combined state, is less than when the element is in the free state since the atomic number of the element is certainly the same whether the element is free or combined.

Experimental results[11] also show that the wave length of the emission lines depends upon the valence of the element. The wave length is longest when the element is in the free state and appears to decrease as the valence increases in the combined state. This again, on the basis of Moseley's law, must mean that the screening constant when the element is in the free state is greater than when it is in the combined state.

By comparing these results with equation (4), it becomes apparent that at the absorption limit the absorption coefficient for an element when in the combined state must be less than when it is in the free state. It seems reasonable to think that the same may be true at any wave length which would explain qualitatively at least, the present results and show that they are in accord with the experiments[4,5,6,11] mentioned above.

Criticism of Experiment and Result

For the work described the balance method is good. However the intensities of the two beams were not exactly the same and changes would necessarily cause errors in the observations. These changes were reduced to a minimum by having similar solutions in each beam. The accuracy of taking slit readings was about 2×10^{-4} in. and of taking density measurements about 2×10^{-4} gm per cc.

[10] Richtmyer, Phys. Rev. **27**, 1 (1926).

[11] Ray, Phil. Mag. **49**, 168 (1925); **50**, 505, (1925).

An obvious suggestion might be that the effect was due to a difference in the scattering before and after reaction, but since the measured effect was the same no matter which solution the beam passed through first it seems very probable that it was not due to a difference in scattering. It is very difficult to say whether the effect was caused by the short or long wave lengths present in the beam.

Conclusions

The results appear to indicate that the x-ray absorption by an element depends upon its valence and therefore upon its state of chemical combination. In the case of Iodine they seem to indicate that its absorption may be greater in the free state than in the combined state.

It gives me great pleasure to thank Professor F. K. Richtmyer for his many valuable suggestions and his keen interest during the progress of this experiment. He suggested the study.

Rockefeller Hall,
Cornell University.
June, 1926.*

* Received February 23, 1927—Editor.

THE HEAT ENERGY OF X-RAYS

By Roy Kegerreis

Abstract

Efficiency of a tungsten-target Coolidge x-ray tube operated at peak voltages from 100 to 200 kv.—The efficiency of x-ray production was experimentally determined for voltages between one and two hundred kilovolts. The high voltage energy input into the x-ray tube was measured by means of an absorption calorimeter. The intensity of the x-rays was measured by means of the temperature rise of a lead absorption cup arranged so that the effects due to scattering and fluorescence of the x-rays as well as effects due to external temperature conditions were eliminated. Elaborate precautions were also taken to suppress electrostatic and electromagnetic induced effects from the high voltage circuits. The efficiency was found to be proportional to the peak voltage. The factor of proportionality was 0.0032 when the efficiency is expressed in percent and the peak voltage in kilovolts.

I. Introduction

THE purpose of the present investigation is to extend our knowledge of the efficiency of x-ray production to the region of high voltage x-rays, 100–200 kv. The general problem of the efficiency of x-ray production has been examined by others, notably by Weeks[1] in 1917, in whose paper an excellent summary of the work prior to that date is given. Since then Ulrey[2] and Kuhlenkampff[3] have also examined the problem. However, the two latter writers used an ionization method to determine the energy of the x-rays. Boos[4] has shown that the ionization is not strictly proportional to the energy absorbed when different wave-lengths are compared. A more reliable method is to measure the heating effect as was done by Weeks. The most recent work on the heat energy of x-rays is by Terrill[5] who has extended the measurements to x-rays excited by a potential of 100 kv. Since much of present day therapeutic work is done with x-rays from a tube excited at 100 to 200 kv it is worth while to extend the measurements to x-rays of such penetrability.

II. Method and Apparatus

In measuring the energy of x-rays care must be taken that none of the energy of the primary beam disappears in any form other than in heat energy absorbed in the calorimeter. This is done by causing the x-rays to pass into a deep cylindrical lead cup. Under these conditions the reflected, scattered and fluorescent x-rays as well as the beta-rays produced by the

[1] Paul T. Weeks, Phys. Rev. **10**, 564 (June, 1917).
[2] Clayton T. Ulrey, Phys. Rev. **11**, 408 (1918).
[3] Helmuth Kulenkampff, Ann. d. Physik, **69**, 548 (June 9, 1922).
[4] B. Boos, Zeits. f. Physik **10**, 1 (1922).
[5] H. M. Terrill, Phys. Rev. **28**, 431, (September, 1926).

primary x-rays are finally absorbed in the lead cup. A diagram of the calorimeter is presented in Fig. 1. The cup was made of lead 1.6 mm thick; such a thickness of lead will absorb at least 99 percent of the x-rays. The x-rays entered the cup through a circular aperture in a lead shield above the absorbing cup. The diameter of the aperture was 4.92 cm. The solid angle subtended by the aperture at the focal spot of the target of the x-ray tube was 0.000622. Four copper coaxial cups surrounded the lead absorbing cup in order to shield it from external temperature changes. Temperature measuring coils and rheostat heating coils are wound on these cups so that their temperatures might be determined and controlled. The resistance of

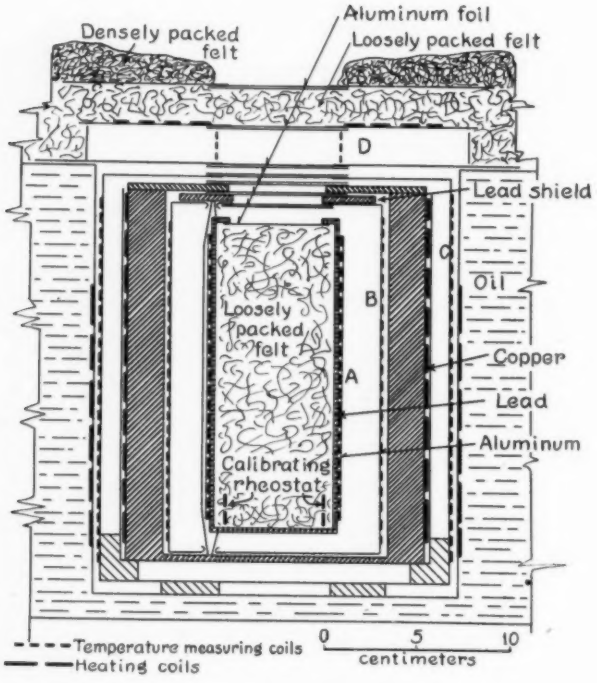


Fig. 1. Diagram of the calorimeter.

each of the temperature measuring coils was about 107 ohms. The outermost cup *C* formed the inner wall of an oil bath which contained about six gallons of transil oil. It was necessary to have a window in the cover of each cup in order to allow the x-rays to enter without undue absorption. All windows were covered with a double thickness of aluminum foil (0.0025 cm thick) with one sheet of the thin paper (1.7 milligrams per sq. cm) between them. The pieces of aluminum foil were closely clamped to the covers of the cups so as to insure good thermal contact. One of the intermediate cups was made with the top and bottom three millimeters thick, the cylindrical walls were double and the intervening space was filled with water. The conductivity and heat capacity were accordingly rather large. The surfaces

of all the cups were polished by buffing. The case which contained the system of cups was covered with two thicknesses of hair felt, one inch thick as shown in Fig. 1.

The entire success of the experiment depends on the maintenance of reproducible temperatures in and about the coaxial cups. The thermal conditions must be constant for all runs. It would be ideal to have exact temperature equilibrium throughout the system of coaxial cups but such a condition is exceedingly difficult to attain because of the very long time required for the heat transfers to take place. It was accordingly decided to set up exactly the same small temperature differences between the various parts at the start of each run. The temperatures of the inner parts were held slightly higher than that of their surroundings. All the parts of the apparatus were maintained at a constant temperature throughout a run except the three inner cups; the absorbing cup warmed up because of the absorption of the x-rays and the two cups immediately exterior to it were warmed by manually controlled heating currents through resistance coils. The conditions were thus nearly but not exactly those of thermal equilibrium.

A small coil (70.70 ohms resistance) which was wound with wire of negligible temperature coefficient of resistance was permanently placed in the bottom of the absorbing cup for calibrating purposes. Heating currents were sent through this coil for one minute out of each five while a calibration was being made.

A Snook Special x-ray machine was used as a source of high voltage. This machine gives a pulsating direct current of 120 pulses per second. As is well known this pulsating current causes static and leakage effects on any other electrical circuits which may be near. Much shielding and non-inductive winding of all coils was employed to minimize these effects but the total elimination of such influences from the results was accomplished only by operating the x-ray tube during an initial period of from one to four hours while equilibrium for constant temperature was being set up, with the residual of all the disturbing influences present. An actual measurement of the heat energy in x-rays was begun by removing a thick lead cover from the orifice in the bottom of the lead-lined box containing the x-ray tube, thus permitting the x-rays to enter the absorbing cup. No changes in the connections were made in the high voltage or Wheatstone bridge circuits when this piece of lead was removed. Constant electrical conditions during the initial period as well as during the run itself were thus unquestionably assured.

The target of the x-ray tube was of tungsten and during the part of the experiment in which the heating effect of the x-rays was being determined the tube was operated in an air space, in a box lined with lead one-fourth inch thick. Electric fans caused currents of air to circulate through the box and over the container of the absorbing cup and about the room generally. Three barriers of thin aluminum foil (0.0025 cm thick) were placed between the target and the box which contained the lead absorbing cup. During a particular run the peak voltage remained constant and was measured by

means of a sphere gap in air. The current through the tube was maintained at 4 milliamperes during all runs.

The intensity of the beam of x-rays was corrected for the absorption which takes place in the glass of the x-ray tube. The absorption was determined from measurements taken with an ionization chamber and a gold leaf electroscope of rays which had passed through a second x-ray tube of the same type. The square root of the fraction of the x-rays transmitted through the two thicknesses of the glass gives the fraction transmitted through one thickness. No correction was made for the absorption by the various thicknesses of aluminum foil. It is a negligible factor in the work since the total thickness is less than 0.05 cm. The absorption by the 40 cm of air which was between the x-ray tube bulb and the absorbing cup was also neglected.

It has been pointed out by Weeks that the high voltage current in an x-ray tube does not follow a sine curve and that therefore the power input cannot be calculated directly from voltmeter and ammeter readings. Weeks determined the power input by measuring the heat produced in the x-ray tube by the bombardment of the target by electrons from the filament. This method was used in the present investigation. The power input was not measured at the same time as the heating effect of the x-rays. Instead a separate experiment was devised to measure the power input when the x-ray tube was operated at each one of a set of different peak voltages and a current of 4 milliamperes. This was accomplished by immersing the x-ray tube in a tank containing 45 gallons of oil The tank was made of wood lined with $\frac{1}{8}$ inch (3.2 mm) lead. The outside of the tank was covered with two layers of hair felt one inch thick. During a run the oil in the tank was kept stirred. The temperature rise per hour for a given voltage on the tube was determined by a mercury in glass thermometer. Correction was made for the heat produced by the filament current by running the filament with no production of x-rays. A curve was then plotted between the temperature rise per hour produced by the bombardment of the target with electrons and the peak voltage. Next a heating coil was placed in the oil and a curve plotted of the temperature rise per hour of the oil tank and the watts input. From these two curves it was possible to determine the relation between the power input into the tube and the peak voltage, the current always being kept at 4 milliamperes.

III. Experimental Results

Typical curves for the heating effect of the x-rays are shown in Fig. 2a. The horizontal portions of the curves (Fig. 2a) represent readings before the x-rays were allowed to enter the absorbing cup, while the sloping portions represent readings when the x-rays were entering the cup. The slope of the rising part of each curve gives a measure of the power absorbed. The slope is expressed in increase in resistance in ohms per hour. The watts computed from the calibration curve of the lead absorbing cup (Fig. 2b)

are a measure of the intensity of the x-rays which pass into the absorbing cup. The actual x-ray energy emitted by the focal spot into the absorbing cup is secured by correcting the value for the absorption in the glass of the

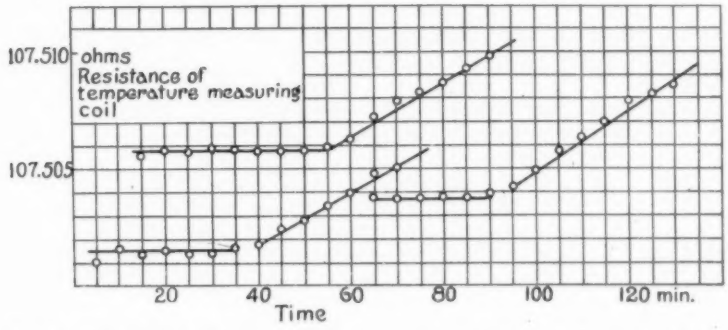


Fig. 2a. Showing the increase in temperature of the calorimeter after the x-rays are allowed to enter.

x-ray tube and also for the shape of the curve for angular distribution of intensity. The total x-ray emission is then secured by multiplying this corrected value by the ratio between the total solid angle about the target

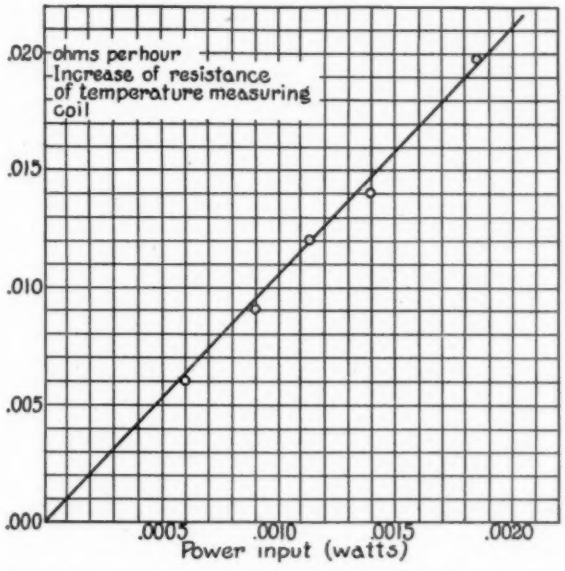


Fig. 2b. Calibration curve for the lead absorbing cup, showing the relation between the power input and the rate of increase in temperature.

and that subtended by the aperture above the absorbing cup. The final results are presented in Table I and in Fig. 3.

In Fig. 3 a curve is plotted between the figures in the third column and the square of the peak voltage. It will be seen that the points fall approxi-

TABLE I

Heat energy of x-rays.

Peak kv.	High voltage input (watts)	Power of x-rays in unit solid angle (watts)	Column 3 / Column 2	Efficiency Column 4 ×2π	Efficiency Column 4 ×4π
98.5	270	0.0796	0.000295	0.18%	0.37%
124.5	335	.101	302	.19	.38
143.3	383	.137	359	.22	.45
161.9	425	.175	413	.26	.52
178.8	462	.203	440	.27	.55
196.3	499	.222	445	.28	.56

mately on a straight line, showing that the x-ray output varies nearly as the square of the applied voltage. Comparing the above figure for the efficiency at 98.5 kv with that obtained by Terrill at 100 kv it is seen that the two results are in fairly good agreement. The fifth column gives the ratio of

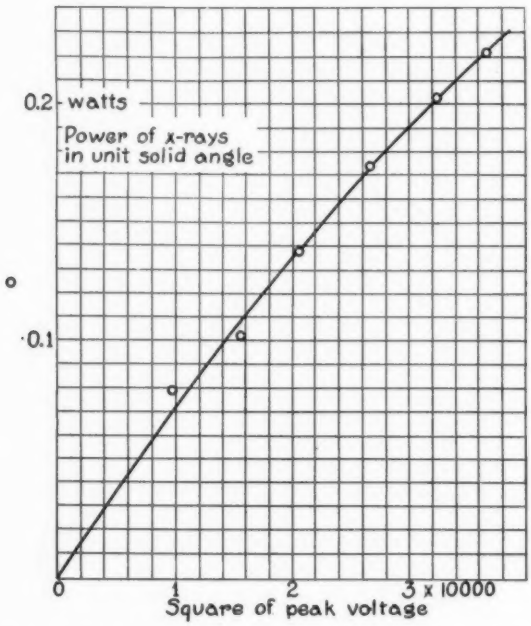


Fig. 3. Variation of the power of the x-rays with the square of the peak voltage.

output to input supposing the intensity to be uniform over the hemisphere exposed to radiation. This is an approximation to the energy actually radiated as x-rays from the tube. The next column gives the preceding multiplied by 2. These are the efficiencies when the x-ray energy absorbed by the target is included in the output. The figures in column 3 are for radiation in the direction of maximum intensity which was only one percent higher than the intensity in a direction perpendicular to the axis of the tube and at an angle of 45° to the target.

It has been shown that the x-ray output varies nearly as the square of the applied voltage. Such a conclusion is also arrived at by Brainin,[6] Ulrey[2] and Kulenkampff[3] who used entirely different methods of measurement.

The values of the efficiency would be considerably increased if the very soft x-rays, which are completely absorbed by the glass of the x-ray tube and the air, were taken into account. (It is to be pointed out that the corrections which were made for the absorption in the walls of the tube apply only to those rays which are transmitted.) The efficiencies that have been found are based on a uniform intensity throughout the total solid angle which surrounds the target. Such an efficiency may be approached in apparatus as a limiting case.

The experiments upon which this report is based were performed in the Physics Laboratory of the University of Michigan.

Chicago, Illinois
December 11, 1927

[6] C. S. Brainin, Phys. Rev. **10**. 461 (June, 1917).

ON THE CALCULATION OF THE SPECTROSCOPIC TERMS DERIVED FROM EQUIVALENT ELECTRONS

By Henry Norris Russell

Abstract

The calculation of the spectroscopic terms which result from an atomic configuration containing several equivalent electrons, in which Pauli's restriction is operative, can be made very simply by the extension of a notation due to Breit. The results are in agreement with those previously given by Hund for p and d electrons and those of Gibbs, Wilber and White for f electrons. Some minor alterations in notation are suggested.

IT IS now well established that the spectroscopic terms belonging to an atom in a given state of ionization depend upon the combined influence of all the electrons outside the complete "shells." When these electrons are unlike (differing in either their total or azimuthal quantum numbers) the determination of the terms produced by any configuration is very simple; but when they are equivalent in these respects, the restriction stated by Pauli becomes operative, according to which no two electrons in the same atom can have the same values for all four of the quantum numbers which define their state. The following method permits a rapid analysis of the effects of this limitation.

The notation is substantially that of Hund's book.[1] The *state of a single electron* in an atom is completely defined by five quantum numbers, s, l, n, m_s and m_l. Of these, s defines the "spin" and is always $\frac{1}{2}$ (in the usual units of $h/2\pi$), l is less by a unit than Bohr's azimuthal quantum number, and n is equal to Bohr's total quantum number. The quantities m_s and m_l are magnetic quantum numbers, giving the orientations of the spin-axis and the orbit plane in a (hypothetical) magnetic field strong enough to break down all couplings between individual orbital or spin vectors; m_s has the value $\pm\frac{1}{2}$, while m_l runs from l to $-l$ by steps of a unit. Pauli's restriction then demands that no two electrons in the same atom have the same values of n, l, m_s and m_l. The small letters, s, p, d, f, $\cdots$, are used to describe electrons for which $l=0, 1, 2, 3, \cdots$; so that, for example, $2s$, $4p$, $3d$, have exactly the same meanings as Bohr's 2_1, 4_2, 3_3.

States of an atom (which correspond to the separate magnetic levels into which a component of a multiple term is divided) may be defined by the numbers S, L, m_S and m_L.[2] Of these, S represents the vector sum of the s's

[1] Hund, Linienspektra und periodisches System der Elemente. Berlin, 1927. (Julius Springer).

[2] Hund uses l_i for the electron and l for the atom; but if both are to be used as subscripts, as is described here, the capital letter appears preferable. The use of s (and S) to denote both spin-vectors and orbits (or terms) is not likely to lead to any misunderstanding, and it is not worth while to change the notation already adopted by several active workers to avoid this formal objection.

and defines the multiplicity, being 0, $\frac{1}{2}$, 1, $\cdots$, for singlets, doublets, triplets, $\cdots$; L is the vector sum of the l's and is 0, 1, 2, 3, $\cdots$, for S, P, D, F, $\cdots$, terms. The magnetic quantum numbers, as ordinarily defined, are in weak fields $m = m_L + m_S$, and in strong fields $m' = m_L + 2m_S$.

When only one electron is active (as in Na I, Ca II, etc), the quantities denoted by small and large letters become identical. In this case a total quantum number n can be assigned to the atomic state. When more than one electron is active, no such assignment is possible, and a complete description of the situation demands the specification of n and l for each electron. For example, the lowest energy-state of Ti I is $(3d)^2\ (4s)^2$, $^3F_2$; two of the four active electrons being in $3d$ orbits, and the other two in $4s$ orbits.

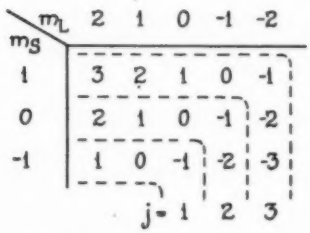


Fig. 1. Relation between m_S, m_L and the inner quantum number j, for a regular ^3D term.

The relation first stated by Pauli, between m_S, m_L and the inner quantum number j[3] has been simply expressed graphically by Breit.[4] The values of m_L are written above the top of a rectangle, those of m_S at the left, and the magnetic quantum numbers $m = m_S + m_L$ inside it. The magnetic levels which unite into a single component of the term in the absence of an external field, are then obtained by dividing the rectangle into L-shaped strips, as shown by the dotted lines in Fig. 1, which corresponds to a ^3D term ($S=1$, $L=2$). The three "runs" of m from 3 to -3, 2 to -2 and 1 to -1 correspond respectively

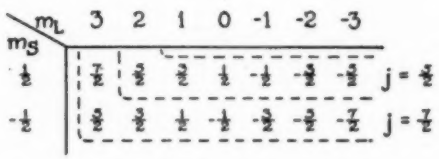


Fig. 2. Relation between m_S, m_L and the inner quantum number j, for an inverted ^2F term.

to the components $^3D_3$, $^3D_2$, $^3D_1$. The maximum numerical value of m in each "run" gives the inner quantum number of the component, in Sommerfeld's notation.

The arrangement here given holds good in general for "regular" terms. For inverted terms, the strips are inverted as shown in Fig. 2, representing a

[3] j is not written as a capital (a) to avoid confusion with Landé's usage, (b) because inner quantum numbers have a meaning only for atomic states, and not for the separate electron-orbits.

[4] Breit, Phys. Rev. **28**, 334 (1926).

^2F term. The same arrangement may be obtained by keeping the strips as before but changing the sign of each individual m_s and m_l.

When two unlike electrons occur in an atom, the values of L and S resulting from the combination of their individual values of l and s may be derived by the aid of Sommerfeld's form of the vector-model, or as Breit has shown, by the graphical process just illustrated. For example, Fig. 1 represents the combination of a p-electron ($l=1$) and a d-electron ($l=2$) provided that the outer vertical and horizontal rows are supposed now to represent the two sets of values of m_l and the quantities inside the rectangle the values of m_L which are obtained by adding the others in all possible conbinations. Dividing them into strips as before we obtain runs of m_L from 3 to -3, 2 to -2 and 1 to -1, which give $L=3, 2, 1$, or D, P, S, terms. If additional electrons (not equivalent to any previously considered) are to be added, the values of m_L for each term of this first resultant are to be combined independently with those of m_l for the new electron.

The s-vectors are similarly treated; thus Fig. 2 represents the addition of an additional electron ($s=\frac{1}{2}$) to a configuration giving a sextet term $S=3$, the new runs of m_S being from $7/2$ to $-7/2$ and $5/2$ to $-5/2$, and the new terms septets and quintets.

So long as the electrons are all dissimilar there is no restriction on these combinations. Any pair of values of m_L, m_l may be added to give a new m_L and any other pair of values of m_S, m_s to give a new m_S. It is therefore sufficient to consider the combinations of the two separately; and terms of any given type (S, P, D) will appear in both the multiplicities produced by adding the new electron.

But when the electrons are equivalent in their total and azimuthal quantum numbers, Pauli's restriction operates. All cases in which both m_l and m_s are the same for a pair of electrons must be excluded, and, what is more, cases obtainable from one another by a mere permutation of the order in which the electrons are counted correspond to the same atomic configuration, and give exactly the same energy-level.

How this works may best be seen by an illustration. In the case of two equivalent p-electrons, the diagram for m_L is as follows.

	1	0	−1
1	[2]	1	0
0	1	[0]	−1
−1	0	−1	[−2]

When $m_S=0$, the individual values of m_s must be $+\frac{1}{2}$ and $-\frac{1}{2}$. The two electrons are dissimilar in this respect, and hence the combination of the m_l's is unrestricted, giving runs of m_L, 2 to -2, 1 to -1 and 0. But when $m_S=1$ (or -1) the two m_s's are alike, and the m_l's are restricted. The values of m_L on the diagonal, which are bracketed above must now be excluded, and the values below the diagonal become mere duplicates of those above. All that remains of m_L is the run 1 to -1.

Collecting these results we have,

$m_S=1$	$m_L=$			
0		2 to −2,	1 to −1,	0
−1			1 to −1	
		^1D	$^3P'$	^1S

We have evidently here exactly the sets of values of m_S and m_L which are required to form the terms indicated at the bottom.

In order to distinguish between primed and unprimed terms a very simple rule which is now being followed by several investigators may be deduced from Heisenberg's statement that, in any electron transition which gives rise to radiation, one electron changes its azimuthal quantum number by one unit, while at the same time one other may change by two. If then we assign to the various types of orbits 0, 1, 2, 3, for s, p, d, f, electrons respectively (which are Hund's values of l) it is evident that the sum of the l's, in any transition, must change from odd to even, or vice versa. This gives us two groups of terms,—even terms (l sums even); S, P', D, F', G, etc.: odd terms (l sums odd): S', P, D', F, G', etc.—which may be distinguished by the fact that the odd terms have an odd number of p and f electrons, taken together, in the configuration. If primed terms are defined in this way, a notation is obtained which is consistent with the accepted notation for the sodium, calcium and aluminum groups, and which may be applied without ambiguity to all cases.

In the case of three p-electrons, the sum $m_S=\pm 3/2$ may be obtained only when all three of the values of m_s are alike. The three values of m_l must then all be different; that is, they must be 1, 0 and −1, and $m_L=0$. The sum $m_S=\frac{1}{2}$ is obtained when two of the m_s's are $\frac{1}{2}$ and the other $-\frac{1}{2}$. The first two give the run 1 to −1 for m_L. Since the third electron is dissimilar (having a different value of m_s) this run combines freely with the m_l of the third electron, giving runs from M_L of 2 to −2, 1 to −1 and 0. The case where $m_s=-\frac{1}{2}$ is exactly similar.

We thus find the array

$m_S=\pm\frac{3}{2}$	$m_L=$		
$\pm\frac{1}{2}$	= 2 to −2,	1 to −1,	0
	$^2D'$	^2P	$^4S'$

Beyond this point we need not go, for, as is well known, a complete shell of six p-electrons must have $m_S=0$, $m_L=0$, giving a ^{1}S term. A shell of five electrons gives the same values as a single electron, and one of four the same as one of two, except that the sign of each individual m_S and m_L is changed, whence it follows that the terms are the same as those previously calculated, but are inverted.

The advantages of the present method of calculation are more apparent in the case of equivalent d-electrons. When discussing it, we will, for brevity, write (4) to denote the "run" 4 to −4, etc. The free combination of any two

runs (m) and (n) (where we may suppose $m \geqq n$), then gives a set of runs $(m+n)$, $(m+n-1)$, and so on to $(m-n)$.

For two d-electrons, we have the diagram

	2	1	0	−1	−2
2	[4]	3	2	1	0
1	3	[2]	1	0	−1
0	2	1	[0]	−1	−2
−1	1	0	−1	[−2]	−3
−2	0	−1	−2	−3	[−4]

When $m_S = 0$ combination is unrestricted, but when $m_S = \pm 1$ the diagonal values must be rejected and the quantities below the diagonal are duplicates of those above, so that we have simply the runs (3) and (1). Our array then becomes

$m_S = \pm 1$	$m_L =$		(3)		(1)	
0	$=$	(4)	(3)	(2)	(1)	(0)
		^1G	$^3F'$	^1D	$^3P'$	^1S

We may next note that, with five d-electrons and $m_s = \pm 5/2$, all the m_s's are of the same sign and m_L must necessarily be 0. With four electrons and $m_s = \pm 2$, only one of the five possible values of m_l is lacking in any set, so then m_L has the run (2) as in the case of a single electron. Finally, for three electrons, and $m_s = \pm 3/2$, two are lacking, and m_L has the runs (3) and (1).

Very little further calculation is now necessary. For three electrons and $m_S = \frac{1}{2}$, we have two with $m_s = +\frac{1}{2}$, giving runs (3) and (1), and one with $m_s = -\frac{1}{2}$, giving the run (2). These runs combine without restriction, giving, in the first case, runs of (1), (2), (3), (4) and (5), and in the second (1), (2) and (3). Here we have

$m_S = \pm \frac{3}{2}$	$m_L =$ (1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)
$\pm \frac{1}{2}$						(1)		(3)
	$^2P'$	^2D	$^4F'$	^2G	$^2H'$	$^4P'$	^2D	$^2F'$

For four electrons, $m_S = \pm 1$ can be obtained from three electrons from which m_s has one sign and $m_L = (3)$ or (1), and one of the other sign, giving the same combinations as before, while when $m_S = 0$, $m_s = +\frac{1}{2}$ for two and $-\frac{1}{2}$ for the other two, giving runs of (3) and (1) to be combined freely with another (3) and (1).

In writing the resulting array, we may record simply the number of runs of m_L of each length found for any given value of m_S, as is done below. The number of terms of the highest multiplicity and of any given sort (S, P, D) is then equal to the number of runs listed under the corresponding value of m_L and in the row headed by the highest value of m_S. The numbers of terms of any lower multiplicity are found by subtracting, from the numbers in the

row headed by the corresponding value of m_S, the numbers in the row next above these.

The results for four and five equivalent d-electrons are shown in Table I. In the latter case, $m_S = \pm 5/2$ gives the single run (0), $m_S = \pm 3/2$ the resultant of runs of (2) for the four similar electrons, and (2) for the other one and $m_S = \pm \frac{1}{2}$ that of (1) and (3) for the group of three electrons and (1) and (3) again for the group of two.

TABLE I

The array for four and five equivalent d electrons.

	m_L	(0)	(1)	(2)	(3)	(4)	(5)	(6)
Four electrons	$m_S = \pm 2$			1				
	± 1		2	2	2	1	1	
	0	2	2	4	3	3	1	1
Five	$m_S = \pm 5/2$	1						
	$\pm 3/2$	1	1	1	1	1		
	$\pm 1/2$	2	2	4	3	3	1	1
Terms		S	P'	D	F'	G	H'	I
Four electrons	Quintets			1				
	Triplets		2	1	2	1	1	
	Singlets	2		2	1	2		1
Five electrons	Sextets	1						
	Quartets		1	1	1	1		
	Doublets	1	1	3	2	2	1	1

Our analysis is now complete. The resulting terms may be arranged in the form shown in Table II.

TABLE II

Resulting terms for equivalent d electrons

d^{10}	^1S		
d, d^9	^2D		
d^2, d^8	$^3P', ^3F'$	^1S ; ^1D ^1G	
d^3, d^7	$^4P', ^4F'$	^2D ; $^2P', ^2D, ^2F', ^2G, ^2H'$	
d^4, d^6	^5D	$^3P', ^3F'$; $^3P', ^3D, ^3F', ^3G, ^3H'$	^1S ^1D ^1G ; $^1S, ^1D, ^1F', ^1G, ^1I$
d^5	^6S	$^4P', ^4F'$; ^4D ^4G	^2D; $^2P', ^2D, ^2F', ^2G, ^2H'$; $^2S, ^2D, ^2F', ^2G, ^2I$

This is identical, in content, with Hund's table[5] but brings out the noteworthy regularities in arrangement in a somewhat different manner. The terms of lowest energy level are found in the second column and the other terms of practical importance in the third.

The case of equivalent f electrons demands a little more reckoning. Two such electrons may be treated in the same fashion as two d-electrons, giving

$m_S = \pm 1$	$m_L =$	(1)		(3)		(5)	
0	$= (0)$	(1)	(2)	(3)	(4)	(5)	(6)
	^1S	$^3P'$	^1D	$^3F'$	^1G	$^3H'$	^1I

[5] Hund, *Linienspektra*, p. 119. The table in his original paper, lacks a ^3G term for d^4 and a ^4S for d^6.

With three electrons, and $m_S = \pm 3/2$, the actual cases must once more be counted, and care must be taken not to count the same combination twice. This may be assured by combining the first two electrons as above and adding a third only when its value of m_L is less than for either of the other two. In this way each permutation will evidently be counted once and only once.

For the two electrons the exhibit of the permissible values of m_l and m_L forms a triangle, as follows.

$m_l=2$	1	0	−1	−2	−3	
$m_L=5$	4	3	2	1	0	3
	3	2	1	0	−1	2
		1	0	−1	−2	1
			−1	−2	−3	0
				−3	−4	−1
					−5	−2

We may begin by combining $M_L=5$ in the first column of the triangle with the values of m_l in subsequent columns and in the outer row above, then the values $M_L=4, 3$, in the next column with the numbers in the *following* columns of the outer row and so on. Thus we get the series of numbers

6, 5, 4, 3, 2;	4, 3, 2, 1;	2, 1, 0;	0, −1;	−2
	3, 2, 1, 0;	1, 0, −1;	−1, −2;	−3
		0, −1, −2;	−2, −3;	−4
			−3, −4;	−5
				−6

which may be immediately rearranged into the runs (6), (4), (3), (2), (0).

For $m_S = \pm \frac{1}{2}$ we have two electrons with m_s of like sign, giving the runs (1), (3), (5), and one of opposite sign with the run (3). The final array may then be written as follows.

m_L	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$m_S = \pm \frac{3}{2}$	1		1	1	1		1		
$= \pm \frac{1}{2}$	1	1	3	3	3	2	2	1	1
Terms	S'	P	D'	F	G'	H	I'	K	L'
Quartets	1		1	1	1		1		
Doublets		1	2	2	2	2	1	1	1

The remaining computations are now straightforward. Four electrons with m_s alike give again the runs (0), (2), (3), (4), (6), five give (1), (3), (5), six give (3) and seven give (0).

The results were worked out independently by Messrs. Gibbs, Wilber and White, and may be found in their paper, (which immediately follows this).

(By mutual agreement, the theory has been presented by one author, and the numerical results, so far as they are new, by the others.)

A word may be said about the notation of the terms corresponding to high values of L. The letter J has been omitted by Hund in accordance with German usage. P and S are preoccupied. The list of letters then becomes

$L=$	0	1	2	3	4	5	6	7	8	9	10
	S	P	D	F	G	H	I	K	L	M	N
$L=$	11	12	13	14	15	16	17	18	19	20	
	O	Q	R	T	U	V	W	X	Y	Z	

Even this extension is barely adequate to include what may be anticipated among the rare earths. The highest multiplicity to be expected is 11, which, as Hund points out[6] should occur in Gd only, and give a term ^{11}F arising from the configuration f^7d^2s, which must be either the normal state or a very low metastable one. The highest value of L among the "middle terms" with one excited electron should occur in the same spectrum, arising from the configuration $(4f)^7\,(5d)^2\,(6p)$, which should give a term for which $m_L=16$, of type ^4V. Similar terms originating in the configuration f^6d^2p or f^8d^2p should occur in Eu and Tb. Still greater values of L could be reached in highly excited states; for example the configuration $(4f)^7\cdot(5f)\cdot(5d)\cdot(6d)\cdot(6p)$ representing an atom of Tb with three excited electrons, should give a maximum value $L=20$, and a term which would demand the notation ^6Z.

Among the multitude of levels given by this configuration would also be some derived from the ^8S term of origin f^7, which would be of multiplicity 12, and all types from ^{12}S to ^{12}L. These terms however would be very unlikely to give lines strong enough to be observable.

In conclusion, reference may be made to the beautiful manner in which Breit's graphical process[4] solves the problem of the limits of series in complex atoms, and shows which components of a given term in the arc spectrum (for example) go to given components of the limiting term in the spark spectrum. The results are naturally in accordance with those given by Hund in Fig. 34 at the end of his book.

PRINCETON UNIVERSITY,
OBSERVATORY,
April 4, 1927.

[6] Hund, *Linienspektra*, p. 177.

TERMS ARISING FROM SIMILAR AND DISSIMILAR ELECTRONS

By R. C. Gibbs, D. T. Wilber and H. E. White

Abstract

Following the scheme of Hund[1] for similar s, p and d electrons the terms arising from similar f electrons have been worked out and tabulated. Tables have also been prepared for one and two electrons, where in the latter case these electrons are dissimilar i.e. have either different total or different azimuthal quantum numbers, and also for three electrons two of which are similar. These tables along with those for similar s, p and d electrons are found not only to be of frequent use but also to bring out certain rules that may be applied in determining spectral terms arising from any electron configuration.

MODERN spectroscopy depends to such a large extent upon the theoretical considerations of space quantization of the electrons in uncompleted shells of the atom that it seemed desirable to tabulate in compact form the terms arising from some of the more frequent electron configurations. Following the arrangement of tables given by Hund[1] for similar s, p and d electrons it has been possible to work out and tabulate the terms arising from one to fourteen f electrons. According to ideas put forward by Landé,[2] Pauli,[3] and others the terms arising from any electron configuration are obtained from all possible combinations of the magnetic quantum numbers m_a and m_s, but Pauli[3] has shown that for similar electrons certain special configurations must be excluded, i.e. two electrons cannot occupy the same orbit at the same time.

TABLE I

Similar s electrons.

(2)	$s-{}^2S$
(1)	$s^2-{}^1S$

Using the notation as proposed by Russell and Saunders[4] and now being widely used, tables have been formulated for some of the more frequently occuring configurations. An electron is denoted by a small letter while

TABLE II

Similar p electrons.

(6)	p^1-	${}^2P$				
(15)	$p^2-{}^1S$		${}^1D$		${}^3P'$	
(20)	p^3-	${}^2P$		${}^2D'$		${}^4S'$
(15)	$p^4-{}^1S$		${}^1D$		${}^3P'$	
(6)	p^5-	${}^2P$				
(1)	$p^6-{}^1S$					

[1] Hund, Zeits. f. Physik **33**, 345 (1925); **34**, 353 (1925).
[2] Landé, Phys. Zeits. **22**, 417 (1921); Zeits. f. Physik **17**, 292 (1923).
[3] Pauli, Zeits. f. Physik **16**, 161 (1923); **31**, 765 (1925).
[4] H. N. Russell and F. A. Saunders, Astrophys. Jour. **61**, 40 (1925).

capital letters are always used for terms. A dot before any small letter signifies that the electron has a different total quantum number than the one preceding it.

TABLE III

Similar d electrons.

(10)	d^1—	$^2(D)$							
(45)	d^2—$^1(SDG)$		$^3(P'F')$						
(120)	d^3—	$^2(D)$		$^2(P'DF'GH')$		$^4(P'F')$			
(210)	d^4—$^1(SDG)$		$^3(P'F')$		$^1(SDF'GI)$		$^3(P'DF'GH')$	$^5(D)$	
(252)	d^5—	$^2(D)$		$^2(P'DF'GH')$		$^4(P'F')$	$^2(SDF'GI)$		$^4(DG)$ $^6(S)$
(210)	d^6—$^1(SDG)$		$^3(P'F')$		$^1(SDF'GI)$		$^3(P'DF'GH')$	$^5(D)$	
(120)	d^7—	$^2(D)$		$^2(P'DF'GH')$		$^4(P'F')$			
(45)	d^8—$^1(SDG)$		$^3(P'F')$						
(10)	d^9—	$^2(D)$							
(1)	d^{10}—$^1(S)$								

The tables given here for similar electrons have all been checked by the combination formula for p things taken q at a time where p is the number of

TABLE IV

Similar f electrons.

(14)	f^1——$^2(F)$					
(91)	f^2—$^1(SDGI)$	$^3(P'F'H')$				
(364)	f^3——$^2(PD'FG'HI'KL')$	$^4(S'D'FG'I')$				
(1001)	f^4—$^1(SDF'GH'IK'LN)$	$^3(P'DF'GH'IK'LM')$	$^5(SDF'GI)$			
(2002)	f^5——$^2(PD'FG'HI'KL'MN'O)$	$^4(S'PD'FG'HI'KL'M)$	$^6(PFH)$			
(3003)	f^6—$^1(SP'DF'GH'IK'LM'NQ)$	$^3(P'DF'GH'IK'LM'NO')$	$^5(SP'DF'GH'IK'L)$	$^7(F')$		
(3432)	f^7——$^2(S'PD'FG'HI'KL'MN'OQ')$	$^4(S'PD'FG'HI'KL'MN')$	$^6(PD'FG'HI')$		$^8(S')$	
(3003)	f^8—$^1(SP'DF'GH'IK'LM'NQ)$	$^3(P'DF'GH'IK'LM'NO')$	$^5(SP'DF'GH'IK'L)$	$^7(F')$		
(2002)	f^9——$^2(PD'FG'HI'KL'MN'O)$	$^4(S'PD'FG'HI'KL'M)$	$^6(PFH)$			
(1001)	f^{10}—$^1(SDF'GH'IK'LN)$	$^3(P'DF'GH'IK'LM')$	$^5(SDF'GI)$			
(364)	f^{11}——$^2(PD'FG'HI'KL')$	$^4(S'D'FG'I')$				
(91)	f^{12}—$^1(SDGI)$	$^3(P'F'H')$				
(14)	f^{13}——$^2(F)$					
(1)	f^{14}—$^1(S)$					

states a given electron may occupy and q the total number of electrons in consideration. This check on the terms shows that in the table given by

TABLE V

One electron systems	*Two electron systems*	
$s \to {}^2S$ ——	$s.s \to {}^1S$	^3S
$p \to {}^2P$ ——	$p\,s \to {}^1P$	^3P
	$p.p \to {}^1(SP'D)$	$^3(SP'D)$
$d \to {}^2D$ ——	$d\,s \to {}^1(D)$	$^3(D)$
	$d\,p \to {}^1(P\,D'\,F)$	$^3(P\,D'F)$
	$d.d \to {}^1(SP'D\ F'G)$	$^3(SP'D\ F'G)$
$f \to {}^2F$ ——	$f\,s \to {}^1(F)$	$^3(F)$
	$f\,p \to {}^1(D\ F'G)$	$^3(D\ F'G)$
	$f\,d \to {}^1(P\ D'F\,G'H)$	$^3(P\ D'F\,G'H)$
	$f.f \to {}^1(SP'D\ F'G\,H'I)$	$^3(SP'D\ F'G\,H'I)$

TABLE VI

Three electrons. (Two similar).

| | | |

the case of three electrons, two similar and one different. The electron configurations given in the above tables include nearly all of the cases that are of primary importance. It may here be pointed out that there is a striking similarity between the terms as given in Table VI and the table of inner quantum numbers as given by Russell and Saunders.[4]

If our present idea is correct for the rare earth group of elements a d electron must be added to the configurations in Table IV to obtain the ground terms of the arc spectra of the corresponding rare earths since in lanthanum a $5d$ valence electron has been added. Furthermore when one of the rare earth atoms is excited the most probable electron to be excited will be an s electron from the already completed $6s$ shell. This means that to the terms in Table IV we must add not only a d electron but also two dissimilar s electrons. It may be seen that the rare earth spectra are likely to be extremely rich in raes-ultimes.

CORNELL UNIVERSITY,
February 15, 1927.

Note added with proof, April 26, 1927. After this paper was submitted for publication we learned from Dr. H. N. Russell that he had independently worked out the terms arising from similar f electrons and that his results check with ours exactly. By mutual arrangement he has given in the preceding paper a detailed explanation of the principles and rules underlying the formation of these tables. The simple rule used by us to distinguish between primed and unprimed terms is given by him on page 785. The ^3G and ^2S terms which we have referred to above as missing in Hund's original paper are included in his book, "Linien Spectren und Periodisches System der Elemente" a copy of which we have just seen.

LINE INTENSITIES IN THE HYDROGEN CHLORIDE FUNDAMENTAL BAND[1]

By D. G. Bourgin

Abstract

Absorption intensities in the lines of the HCl fundamental band for tube-lengths from 0.0998 to 2.97 cm.—The transmission of columns of HCl 0.0998, 0.169, 0.248, 0.54, 0.996, and 2.97 cm long in the region of its fundamental vibration-rotation band at 3.5μ was measured with a bismuth-silver vacuum thermopile. The light was resolved by a quartz spectrometer. The curves give indirect evidence of the isotopic doubling and yield fairly accurate absolute and relative values of the intensities of the absorption lines. The values given are checked by several independent methods of calculation. The results confirm the predicted asymmetry in the intensities of corresponding lines in the P and R branches as suggested by Kemble's theory, the summation rule, and the new formulation of the quantum theory, and, further, verify the quantitative predictions of these theories when the statistical weights are suitably chosen. The particular choice favored by the data is the selection $p_M = 1, 3, 5, \cdots$, if the lines are assumed to be singlets (and $p_M = 2, 4, 6, \cdots$, if the lines are assumed to be spectroscopic doublets on the presumption that the summation rule is valid for this case). The lines are apparently narrower and deeper than heretofore supposed, and it is demonstrated that the exponential law of transmission is not applicable to the transmission curves even after these have been corrected by the usual slit-width correction formulas.

Einstein probability-of-transition coefficients.—The calculated values of the Einstein probability-of-transition coefficients are $B_{0,1} = 5.1 \times 10^{15}$ for the first line of the positive branch and $A_{0,1} = 58$ for the first line of the negative branch. These values are in harmony with estimates based on the correspondence principle.

Variation of the molecular moment with nuclear displacement.—The most plausible value of the variation of the molecular moment with nuclear displacement as determined for the region of the equilibrium position is 0.828×10^{-10} e.s.u. The combination of the measurements of this paper with Zahn's data on the dielectric constant of HCl yields more reasonable results when the calculations are made in accordance with the new quantum theory or classical theory than when the older forms of the quantum theory are used.

Introduction

THE recent and more precise developments of the quantum theory have focussed attention on the intensities of spectral lines in emission and absorption. Although the pioneer experiments at Utrecht and elsewhere have afforded intensity data for atomic systems, it appears that no corresponding quantitative work from this point of view has been done in the molecular field. The experimental part of this paper presents the results of an investigation of the absorption lines of HCl in the region of its fundamental band in the infra-red at 3.5μ.

[1] E. C. Kemble and D. G. Bourgin, Nature **117**, 789 (1926); D. G. Bourgin and E. C. Kemble, Phys. Rev. **27**, 802 (1926).

In accordance with general usage, the term absorption intensity of a line M is taken to mean the integral of the absorption coefficient taken over the absorption line and is written

$$\alpha_M = \int_M \mu(\nu)\, d\nu \tag{1}$$

where $\mu(\nu)$ is the absorption coefficient expressed as a function of the frequency. The subscript M takes on negative values for the P branch of the band and particularizes the Mth line counting from the missing central component.

Absorption curves for the HCl fundamental band have been obtained for long tube-lengths by several experimenters.[2] The most accurate results are those of Imes[3] and of Brinsmade and Kemble[4] whose researches were carried out primarily to determine the positions, rather than the intensities, of the lines. In all published spectroscopic investigations[2-8] of the fundamental absorption region of HCl, the measurements have been obtained for a single long gas-column. The unpublished thesis of Brinsmade and the recent indirect evidence adduced by Kemble[9] indicate the possibility that the exponential law is inapplicable to the observed measurements. This conclusion is directly confirmed by the experiments reported in this paper. Hence it is not possible to estimate either the absorption coefficient for a particular frequency or the integrated value of the coefficient from data on a single tube-length.

For the case of the simple vibration-rotation bands under which the fundamental band of HCl is to be classified the following theoretical formula has recently been proposed by Kemble[9]

$$\alpha_M = (c/\nu^3)\bar{p}_M e^{-W_M/kT} \tag{2}$$

where ν is the frequency associated with the transition giving rise to the line, the exponential factor is the Boltzman factor taken for the initial state and $\bar{p}_M$ denotes the arithmetic mean of the a priori probabilities involved in the transition. Kemble's derivation of Eq. (2) is based on a splitting up of the stationary states of the molecule by a hypothetical weak magnetic field and the assumption that the sum of the intensities of the simple Zeeman components passes continuously into the intensity of the band line as the strength of the magnetic field approaches zero.

The measurements of the intensities of lines in atomic spectra have suggested the empirical, so-called "summation rule."[10] The rule has since

[2] Burmeister, Verh. d. D. Phys. Ges. **15**, 589 (1913).

[3] E. S. Imes, Astrophys. J. **1**, 251 (1919).

[4] J. Brinsmade and E. C. Kemble, Proc. Nat. Acad. Sci. **3**, 420 (1917).

[5] E. von Bahr, Verh. d. D. Phys. Ges. **21**, 115 (1913).

[6] Colby and Meyers, Astrophys. J. **53**, 300 (1921).

[7] Colby, Meyers and Bronk, Astrophys. J. **57**, 7 (1923). (The last two papers give only the positions of the absorption maxima and not the entire absorption curve.)

[8] G. Becker, Zeits. f. Physik **34**, 255 (1925).

[9] E. C. Kemble, Phys. Rev. **25**, 1 (1925).

[10] N. Burger and H. B. Dorgelo, Zeits. f. Physik **23**, 258 (1924).

been justified on theoretical grounds.[11,12] Its extension to band spectra leads to an expression of the same general form as Eq. (2) except that the form of the frequency factor is left undetermined. Also the analogue, on the basis of the summation rule, of the probability factor in Eq. (2) takes on a different set of values for an arbitrary choice of statistical weights from that taken on by the term occuring in Eq. (2).

The new quantum theory introduced by Heisenberg and Born suggests that the intensity of the Zeeman component correlated with the transition $m \rightarrow m \pm 1$ and $r \rightarrow r \pm 1$, where m and r are the rotational and spatial quantum numbers respectively, is proportional[13,14] to $(m \pm r)\ (m \pm r - 1)/(m^2 - \frac{1}{4})$. The intensity for the transition $m \rightarrow m \pm 1$, $r \rightarrow r$ varies as $(m^2 - r^2)/(m^2 - \frac{1}{4})$. It may be shown that a summation over all allowed values of r and application of the Kemble, Heisenberg postulate of the continuity of intensities[9,11] leads to a linear dependence on the rotational quantum number in harmony with (2).

The experimental verification of Eq. (2) and the resolution of the ambiguity[9,12,15] as regards the exact variation of the probability factor (and therefore the proper choice of weight factors) are important consequences of the present work.

The procedure adopted for evaluating the integrated absorption coefficients consisted in obtaining the absorption curves for six different absorbing columns varying in length from 0.0988 cm to 2.97 cm. Curves were drawn of the areas under the absorption lines plotted against tube-length. The gas columns were sufficiently short to permit of reasonably accurate extrapolation of these curves to zero tube-length. The initial slopes of these extrapolated curves, as will appear later, yield the desired absolute integrated absorption coefficients.

Experimental Work

The HCl gas was obtained by dropping concentrated sulphuric acid on constant boiling HCl solution. Five Emmerling absorption towers were used to purify the gas and every precaution was taken to avoid its contamination.

The infra-red spectrometer was the quartz prism instrument constructed by Brinsmade and used by Brinsmade and Kemble. A variety of modifications in the details of the apparatus gave increased sensitivity and steadiness. It was of the Wadsworth[16] constant deviation type as modified by Gorton.[17] Fig. 1 shows a diagram of the optical system. The instrument

[11] W. Heisenberg, Zeits. f. Physik **31,** 617 (1925).

[12] R. H. Fowler, Phil. Mag. **50,** 1079 (1925).

[13] D. M. Dennison, Phys. Rev. **28,** 318 (1926).

[14] I. Tamm, Zeits. f. Physik **37,** 685 (1926). Dr. Tamm seems to infer incorrectly that neglecting the Boltzman factor the band intensities are practically independent of the rotational quantum numbers and follow the Maxwell-Boltzman distribution law.

[15] G. H. Dieke, Zeits. f. Physik **33,** 161 (1925).

[16] Wadsworth, Phil. Mag. **38,** 137 (1894).

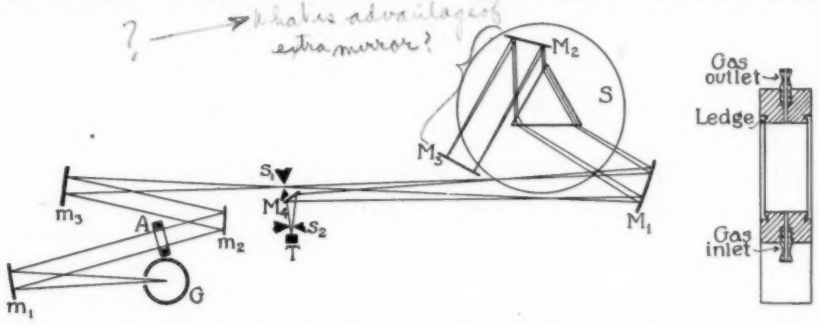
[17] Gorton, Phys. Rev. **7,** 66 (1916).

was provided with a 60° quartz prism having faces 5.1 cm high and 4.3 cm wide. The focal length of the concave mirror M_1 was 50 cm. The extreme spectral range falling on the thermopile slit was computed to be 126A, with both slit widths set at 0.3 mm.

The receiving instrument was a twenty junction bismuth silver vacuum thermopile constructed by Coblentz. Every effort was made to rid the thermopile case of occluded gas by long continued pumping.

The galvanometer was a Weston gravity controlled d'Arsonval type of instrument. The sensitivity was usually adjusted to a value between 2×10^{-8} and 8×10^{-9} volts per mm at a meter's scale distance.

A Nernst glower actuated by a steady alternating current was used as a light source. Direct current from storage batteries was used to run a



Figs. 1 and 2. Optical plan of set-up. G, Nernst glower; m_1 and m_3, concave mirrors; m_2, M_3, M_4, fixed plane mirrors; M_2, plane rotating mirror; M_1, collimating mirror; s_1, entrance slit; s_2, thermopile slit; T, thermopile; A, absorption chamber.

high-frequency motor-generator loaned to the writer by Professor G. W. Pierce. The usual variation in mean square current over a period of three or four hours was less than 0.005 amp.

The first absorption tube consisted of two brass frames between which cylinders of various lengths could be fitted. All the absorption tubes were fitted with quartz windows about 2 mm thick. The three shortest tubes (Fig. 2) were specially designed to permit an accurate measurement of the length of the absorbing column. The tubes were made of brass and an annular depression was cut around each window ledge. The windows were sealed in place by means of a ring of de Khotinsky cement placed on this depression. By this method it was possible to keep the window ledges perfectly clean so that the length of the tube could be measured by micrometering the distance between the ledges with the quartz plates removed.

The necessary data were (1) the transmission, T_1, of the tube itself free from gas, and (2) the transmission, T_B, of the gas-filled tube. In terms of these transmissions the gas absorption is

$$1-T_1/T_B \qquad (3)$$

The tube transmission will be referred to as the "base-line," the precise determination of which presented a rather difficult problem. A difference

of the order of 0.5 percent was found for the variation in transmission of a 65 cm tube when filled with room air and when evacuated. Therefore, for the tube-lengths used in this research, the transmission of the air-filled tube could be used as the base-line. The stumbling block was the removal of all trace of gas from the absorption chamber since merely blowing or sucking air through was ineffective.

Four distinct methods of obtaining data to fix the base-line were followed and will be distinguished by the letters (*a*), (*b*), (*c*) and (*d*). For the 0.96 cm and 2.97 cm tubes, the procedure (*a*) was the following: Preliminary to the first run on either tube the two window frames, with the windows already attached, were mounted a distance apart equal to their separation with the particular brass cylinder to be used in the run and about eight base points were obtained in the region to be covered. The windows were purposely not treated to remove adsorbed gas since it was essential that the condition of the surfaces be the same as when the cylinder was in place and the tube filled with gas. This adsorption was quite apparent for, even after the exposure of the quartz windows to the air for a half-day, slight warming was sufficient to liberate enough gas to give off the sharp characteristic odor of HCl. The base-line having been determined, the glower the mirror and the stops which secured proper alignment were not varied till the run had been completed. The whole band could generally be covered in two runs (or three runs at most), therefore, for the second run the base-points were determined at the end of the run. This method of fixing the base-curve solved the problem of minimizing the inaccuracies due to the presence of occluded gas on the windows.

Method (a) was inapplicable to the shorter tubes which were constructed of a single brass plate. For two of the four runs on the 0.169 cm tube, the base-line was determined before and checked after the run, by evacuating the tube. This was method (*b*). For the other two runs and for the runs on the 0.248 cm tube and the run on the 0.0988 cm tube covering the negative branch, the procedure (*c*) was to determine the base-points for the positions of minimum absorption as these low absorption points were reached during the course of the experiment, a large capacity piston pump being used to take out most of the gas and the exhaustion then improved by cutting out this pumping unit and replacing it with a Cenco "Hyvac" oil pump. This method reduced the inaccuracies introduced by progressive variations during the course of the run and in the event of some sudden change limited the possibility of error to one line instead of casting suspicion on all the values of the run. In the case of the run on the positive branch with the 0.0988 cm tube, readings were taken at each point with the tube alternately evacuated and filled with gas. In this method (*d*) the tube was not moved at all and the true transmission was immediately given as the ratio of the successive readings when the tube was filled with gas and when it was pumped down. If the gas could be completely removed in a conveniently short time this method would be the most satisfactory inasmuch as it eliminates the intermediate step of obtaining the values of the glower

emission. The method is most successful when the volume to be evacuated is a minimum, which explains its use for the shortest tube-length. Because of possible unforseen complications in the way of window-adsorption effects, it seemed advisable to limit the use of this plan to the one tube-length and test its value by the plausibility of the results obtained as compared with those for the other tube-lengths.

The spectrometer settings were read on a revolution counter and dial. In general, the interval used was about one dial revolution (the absorption peaks were about six turns apart near the center of the band) except in the neighborhood of the maxima where sometimes quarter revolutions were used.

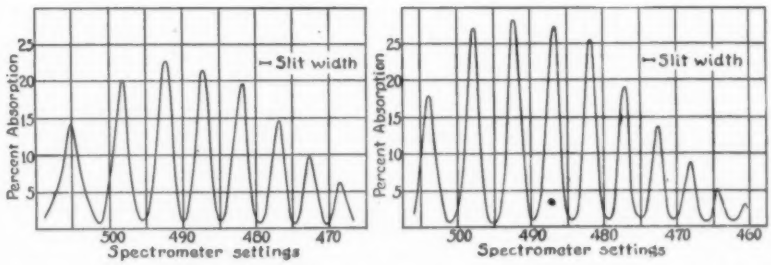
In calculating the absorption from the experimentally determined diminution in light intensity, it was assumed that the effects of selective scattering and selective reflection at the quartz-gas interface were neglible. As the curves of total absorption (area under peak) plotted as a function of the tube-length extrapolate naturally to the value zero for zero tube-length, it hardly seems possible that there could have been any appreciable selective reflection. The writer has no definite check on the assumption that scattering may be neglected, but since the selective scattering should be proportional to the absorption it is not likely that it could effect, markedly, the apparent relative absorption intensities of the different lines.

Theory of the Calculations

The general plan for obtaining the integrated absorption coefficients has already been suggested in the introduction and it has been pointed out that the procedure involved the determination of the area under each absorption line for several tube-lengths. On denoting these areas, when measured in frequency units, by the symbol $A_M(x)$ it is possible to write

$$A_M(x) = \int_M [(T_B - T(x))/T_B]d\nu \tag{4}$$

where T_B is the base-line transmission and $T(x)$ is the transmission of the gas-filled tube of length x. Strictly speaking the absorption curve for a



Figs. 3A and 3B. Characteristic absorption curves taken with 0.169 cm and 0.248 cm tubes. R branch.

given line extends from $\nu = 0$ to $\nu = \infty$ but the estimates were made on the assumption that the true area was closely approximated by the area under

the experimental curves, uncorrected for slit width, included between two successive minima separating the line in question from its neighbors (cf Figs. 3A and 3B).

With regard to the neglect of the overlapping of adjacent lines, it may be pointed out that (a) adjacent lines do not differ greatly in intensity and the overlapping of lines of equal intensity clearly leads to no error, (b) in the region where the intensities might be considered as changing comparatively rapidly the net gain from the more intense neighbor is, in general, very nearly balanced by the net loss to the less intense adjacent line, and (c) for the very short tube-lengths employed in these experiments, the intensity in the region between absorption lines is quite small.

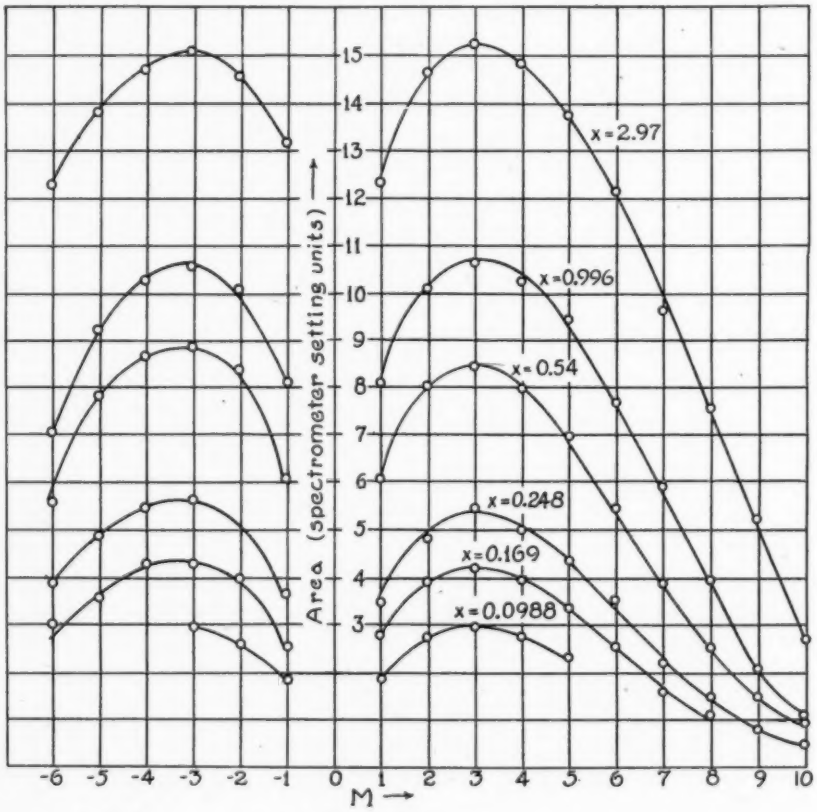


Fig. 3C. Smoothing curves.

The areas under the various absorption maxima were measured from the original curves without correcting for slit width. Clearly, since the area under any line regardless of slit width gives the fractional amount of light abstracted from a beam whose intensity is independent of frequency, the areas should not be affected by variations in the slit width which do not lead to serious overlapping.

For estimating the areas under the absorption curves large scale plots similar to Figs. 3A and 3B were used. A sufficient number of points were available for the lines, usually about seven or eight at least, to indicate the general appearance though, of course, there was some latitude in defining their shapes. For most of the tube-lengths several sets of overlapping data were available and the absorption data used in the calculations are the averages of these for each tube-length.

In the adaptation of the measured areas to the calculations a preliminary smoothing process was resorted to in order to reduce the inaccuracy in the individual lines. The smoothing was effected by drawing the best curve through the correlated points in a plot of line-number against line-area (Fig. 3C). In all the calculations based on direct application of the "five-term polynomial" method and in all methods involving use of the data for the line $M=3$ a second smoothing occurred in the choice of the most plausible curve through the points in the plots of area against tube-length of which Fig. 4 is the type.

TABLE I

Smoothed areas in frequency units.

M	2.97 cm	.996 cm	.54 cm	.248 cm	.169 cm	.0988 cm
1	1.178	.767	.574	.346	.265	.175
2	1.423	.979	.777	.484	.379	.262
3	1.526	1.071	.845 (?)	.536	.415	.292
4	1.536	1.063	.826	.526	.401	.284
5	1.405	.986	.726	.455	.348	.236
6	1.317	.825	.581	.359	.270	
7	1.078	.643	.424	.257	.186	
8	.848	.433	.284	.166	.108	
9	.605	.287	.167	.088		
10	.329	.124	.103	.0509		
−1	1.172	.737	.559	.328	.238	.166
−2	1.285	.884	.731	.449	.345	.232
−3	1.285	.900	.754	.478	.374	.253
−4	1.225	.853	.717	.454	.345	
−5	1.103	.744	.623	.393	.292	
−6	.956	.551	.470	.300	.210	

The original areas were in units of percent and spectrometer settings. To change to a frequency standard two independent methods were employed to estimate $\Delta\nu/\Delta\theta$ where θ refers to the dial settings and ν to the frequency. In the first method this ratio was calculated from the prism-angle and the known dispersion curve of quartz. In the second method the values of $\Delta\theta$ for successive absorption maxima as determined from the experimental plots similar to Figs. 3A and 3B and the corresponding values of $\Delta\nu$ as given by Colby and Meyers,[6] were plotted against line number M. The ratios of the values of the ordinates of the two curves for any value of M is the correlated value of $\Delta\nu/\Delta\theta$. The agreement of the two sets of values was quite good for the positive branch, although there was a slight departure for the negative branch. The mean of the two estimates was used in the calculation.

The primary purpose of the experiments was to determine the values of α_M for the various lines. It may immediately be shown that if we plot the area under an absorption line as a function of the tube-length x, α_M should be the slope of the curve at $x=0$. Thus, from the fundamental relation between the absorption coefficient and the intensity $I(\nu)$

$$dI(\nu) = -\mu(\nu)I(\nu)d\nu \tag{5}$$

we obtain

$$A_M(x) = \int_M (1-e^{-\mu(\nu)x})d\nu \tag{6}$$

which gives immediately

$$(dA_M/dx)_{x=0} = \alpha_M = \int_M \mu(\nu)d\nu \tag{7}$$

The evaluation of the initial slopes of the various graphs of area against tube-length required by Eq. (6) is somewhat complicated by the large curvature near the origin. Several methods of attack were employed in the attempt to get as accurate a solution of the problem as possible.

The first of these methods consisted in fitting the five-term polynomial formula

$$A_M(x) = \omega^{(1)}x + \omega^{(2)}x^2 + \cdots + \omega^{(5)}x^5 \tag{8}$$

to the data. This method is inaccurate since it accentuates the influence of the shorter tube-lengths in that a very small error in the area for the shortest tube produces a large error in the calculated value of $\omega^{(1)}$ or α_M.

A method which eliminates this difficulty is most easily explained if we start from the crude assumption that the absorption coefficient curves ($\mu(\nu)$ plotted against ν) for the various lines have the same shape so that by suitable change in the scale of ordinates any curve could be superposed on any other. This assumption is expressed by

$$\mu_M(\nu) = K_M F[\nu - (\nu_0)_M] \tag{9}$$

where $(\nu_0)_M$ is the frequency of the center of the Mth line. If it were true, $A_M(x)$ would be a function of the product $K_M x$ or, what comes to the same thing, of $\alpha_M x$. Then if we consider two points corresponding to the same ordinate A on curves for different lines, this product must be the same for both. In other words for two such points

$$x_{M'}/x_M = \alpha_M/\alpha_{M'} \tag{10}$$

Hence the ratio of the integrated absorption coefficients for any two values of M could be determined by plotting curves of area against tube-length like the one of Fig. 4, and comparing the abscissas of any two points with equal ordinates.

This method of procedure leads, in practice, to values of $\alpha_M/\alpha_{M'}$, which vary with the ordinate (area) for which they are calculated, showing that

the lines are not exactly the same in shape. This is to be expected since HCl is a mixture of the constituents HCl_{35} and HCl_{37} so that each absorption line is an isotopic doublet. The separation of the doublet components depends on the rotational quantum numbers[18] and therefore varies with M.

The variation of $x_{M'}/x_M$ with the corresponding ordinate A is not rapid for small values of A, however, and since

$$\operatorname{Lim}_{A\to 0}\frac{x_{M'}}{x_M}=\operatorname{Lim}_{x_M\to 0}\frac{x_{M'}}{x_M}=\frac{\alpha_M}{\alpha_{M'}} \tag{10.1}$$

it follows that the extrapolation of the $x_{M'}/x_M$ values to zero A (or zero x_M) gives an accurate method of evaluating the *relative* absorption coefficients.

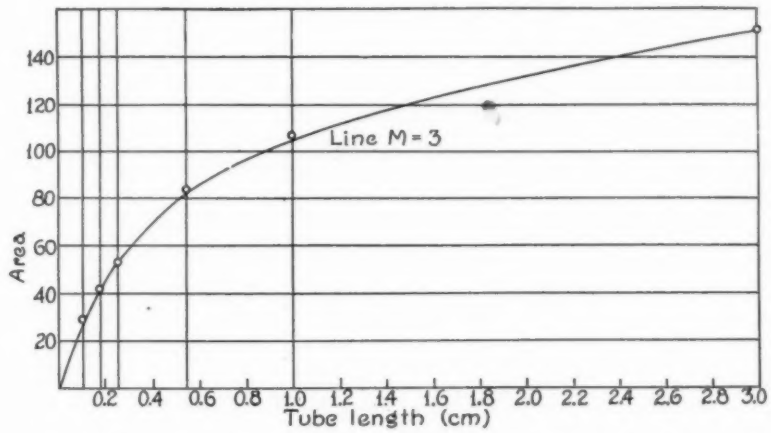


Fig. 4. Curve showing the variation of line area with tube-length.

In applying this method the line $M=3$ was arbitrarily selected as a standard of comparison and an accurate curve was drawn through the points defined by corresponding values of smoothed area and tube-length (Fig. 4). For any other absorption line M each area obtained from a run using a gas column of length x_M was used to determine a value x_3 for which the ordinate of the standard curve was equal to the area in question. Then the values of the ratio x_3/x_M were plotted against x_M for each absorption line. These lines would have been straight lines, with ordinates equal to the relative absorption coefficients desired, if the shapes of all the lines had been the same. It is evident from Fig. 5 that the extrapolation to the axis of ordinates is a fairly safe one.

In view of the appreciable experimental errors, it is desirable to have some theoretical guide for drawing "best curves" for x_3/x_M. Such a guide will be suggested by the following analysis. The absorption coefficient may be written

$$\mu(\nu)=\mu'(\nu-\nu_1)+\mu''(\nu-\nu_2) \tag{11}$$

[18] R. S. Mulliken, Phys. Rev. **25**, 119 (1925).

where $\mu'(\nu-\nu_1)$ and $\mu''(\nu-\nu_2)$ are the respective contributions of each isotope and ν_1 and ν_2 are the frequencies of the absorption maxima for the corresponding isotopes. It will be brought out that the form of the absorption curves is determined by the magnitude of the terms

$$\int_M \mu(\nu)^n d\nu = \int_0^\infty \left\{\mu'(\nu-\nu_1)+\mu''(\nu-\nu_2)\right\}^n d\nu \tag{11.1}$$

The expansion of $A_M(x)$ leads to the series

$$A_M(x) = \mu_M{}^{(1)}x - \mu_M{}^{(2)}x^2/2! + \mu_M{}^{(3)}x^3/3! \cdots \tag{12}$$

where

$$\mu_M{}^{(j)} = \int_M \left[\mu_M(\nu)\right]^j d\nu$$

Let us make the assumption expressed in Eq. (9), then substituting $x' = xK_M/K_3$ in Eq. (12) gives for the expansion of A_M in terms of x'

$$A_M(x) = \mu_M{}^{(1)}K_3x'/K_M - \mu_M{}^{(2)}\left\{K_3x'\right\}^2/K_M{}^2 2! + \mu_M{}^{(3)}\left\{K_3x'\right\}^3/K_M{}^3 3! \tag{12.1}$$

If the assumption made about the factorization of the absorption coefficient into a term dependent on the quantum numbers and another independent of the line were true (vide Eq. 9) it is seen that the coefficients of the various powers of the primed variables in Eq. (12.1) would be identical with those in the expression of $A_3(x)$ in powers of x. Actually, from the fact that $\partial\left[\mu'(\nu-\nu_1)\right]/\partial\nu$ (or $\partial\left[\mu''(\nu-\nu_2)\right]/\partial\nu$) is of one sign from 0 to ν_1 (or ν_2) and from ν_1 (or ν_2) to ∞ and the knowledge that $\mu'(\nu-\nu_1)$, $\mu''(\nu-\nu_2)>0$ it may be shown analytically or made evident graphically, that the integral $\int_0^\infty\left[\mu(\nu)\right]^n d\nu$ for $n>1$ steadily diminishes on increase of the isotope separation. An equivalent statement is that for lines for which $(\Delta\nu)_M>(\Delta\nu)_3$, where $\Delta\nu$ is the isotope separation, the following inequality holds

$$\mu_M{}^{(j)}\left\{K_3/K_M\right\}^j < \mu_3{}^j \tag{9.1}$$

The sign of the inequality is reversed if $(\Delta\nu)_3>(\Delta\nu)_M$.

(12) Inverting the series gives

$$x = a_M{}^{(1)}A_M + a_M{}^{(2)}A_M{}^2 + \cdots + a_M{}^{(j)}A_M{}^j + \cdots \tag{12.2}$$

Eq. (12.2) may be employed to yield the rigorous value of the ratio x_3/x_M. Thus

$$x_3/x_M = \frac{a_3{}^{(1)}A + a_3{}^{(2)}A^2 + \cdots}{a_M{}^{(1)}A + a_M{}^{(2)}A^2 + \cdots}$$

where x_3 and x_M are the values of x correlated with a given value of $A(x)$ (the subscript M or 3 would have no significance here) for the line $M=3$ and for the Mth line respectively. Expanding the ratio in powers of A and then replacing A by its expansion in terms of x_3 or x_M yields

$$x_3/x_M = \frac{a_3^{(1)}}{a_M^{(1)}}\left\{1+\mu_3^{(1)}x_3\left(\frac{a_3^{(2)}}{a_3^{(1)}}-\frac{a_M^{(2)}}{a_M^{(1)}}\right)+\left(\left\{\mu_3^{(1)}\right\}^2-\mu_3^{(2)}\right)x_3^2\right.$$
$$\left.\left[\left\{\frac{a_3^{(3)}}{a_3^{(1)}}-\frac{a_M^{(3)}}{a_M^{(1)}}\right\}-\frac{a_M^{(2)}}{a_M^{(1)}}(\quad)\right]+\cdots\right.$$
$$=\frac{a_3^{(1)}}{a_M^{(1)}}\left\{1+\mu_M^{(1)}x_M\left(\frac{a_3^{(2)}}{a_3^{(1)}}-\frac{a_M^{(2)}}{a_M^{(1)}}\right)+\left(\left\{\mu_M^{(1)}\right\}^2-\mu_M^{(2)}\right)x_M^{(2)}\right.$$
$$\left.\left[\{\cdots\}-\frac{a_M^{(2)}}{a_M^{(1)}}(\quad)\right]+\cdots\right.$$

where the $\mu_3^{(i)}$, $\mu_M^{(i)}$ coefficients occur in Eq. (12) and it is evident that

$$\operatorname*{Lim}_{x_M\to 0} x_3/x_M = \operatorname*{Lim}_{x_B\to 0} x_3/x_M = a_3^{(1)}/a_M^{(1)} = \mu_M^{(1)}/\mu_3^{(1)}$$

The coefficients $a_3^{(i)}$ and $a_M^{(i)}$ of the inverted series (12.2) are such functions of $\{\mu_M^{(i)}\}$ that if the distinction were dropped between $\{\mu_M^{(1)}\}^i$ and $\mu_M^{(i)}$ the ratio $a_M^{(i)}/a_M^{(1)}$ would reduce to unity. (For instance $a_M^{(1)}=1/\mu_M^{(1)}$, $a_M^{(2)}=-\mu_M^{(2)}/\{\mu_M^{(1)}\}^3$).

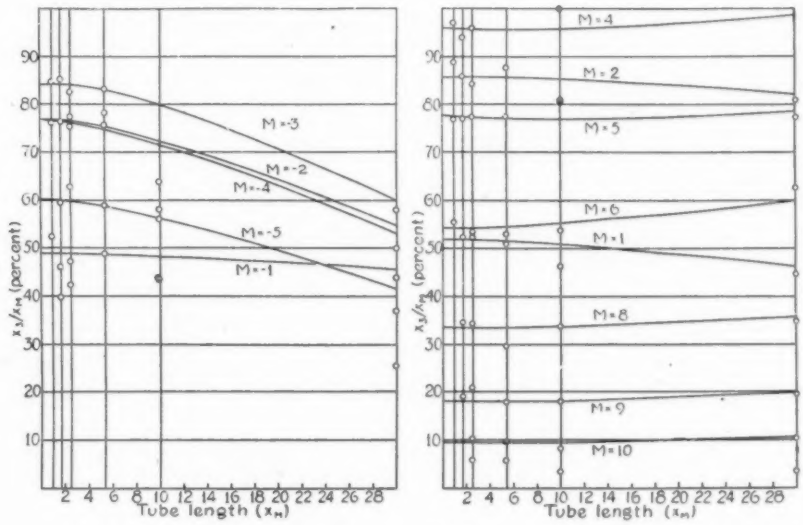


Fig. 5. Extrapolation plots for the "ratio" method.

It is, therefore, easily understood that the assumption of Eq. (9) would lead to the equality of the ratios $a_M^{(i)}/a_M^{(1)}$ and $a_3^{(i)}/a_3^{(1)}$ and this would carry with it the vanishing of all the terms in powers of the variable in Eq. (13). The isotope doubling disturbs the equality of $a_M^{(i)}/a_M^{(1)}$ and $a_3^{(i)}/a_3^{(1)}$ and the inequality of Eq. (9.1) points to the conclusion that the x_3/x_M *vs* x_M curves should be concave upwards for $3<M$ and concave downward for $M<3$, (at least initially.)

Although the rotational isotope separation is essentially a quadratic function of the quantum numbers, the resultant of the vibrational and rotational isotope separations may be considered as varying very nearly linearly in the region of the band center. Bearing this in mind, it is clear that since the values of A for the lines $M=7$, 8, 9, 10 were quite small for all the tube-lengths used the influence of the higher order terms in Eq. (13) would not be expected to be pronounced, but in the case of the negative branch where the areas are larger for lines equally far removed from the line $M=3$, the curvature should be more noticeable.

To determine the value of x_3 correlated with a given area, it was necessary to approximate the curve of area against tube-length for the line $M=3$ with some care. Two methods in particular were used for this purpose. One of these is discussed in some detail under the heading of Method III; the other, which will be referred to as Method II, utilized formula (8) to locate points corresponding to tube-lengths 0.01 cm, 0.02 cm, etc.

TABLE II

Interpolated values of areas.

Method II		Method III		Method IV	
x_3 (cm)	$A(x)/12.28$ $\times 10^{-12}$	x_3 (cm)	$A(x)/12.28$ $\times 10^{-12}$	x_3 (cm)	$A(x)/12.28$ $\times 10^{-12}$
0.01	0.3697	0.0323	1.103	0.01	0.37
0.02	0.716	0.0645	2.001	0.1	2.9
				0.2	4.67
0.04	1.346	0.129	3.42		
0.08	2.276	0.323	6.25		
		0.645	8.95	1.0	1.065
		1.29	12.2	2.0	13.5

Method III proceeds as follows: since the value of $\int_M(1-\exp(-\mu(\nu)x))d\nu$ is only slightly affected by changes in the functional form of $\mu(\nu)$, whose influence is perceptible only when the integrand is quite small, one is prompted to use as a simple approximation

$$\mu(\nu)=\frac{a_M}{(\nu-\nu_1)^2+b_M{}^2} \tag{14}$$

where a_M and b_M are certain characteristic constants. Therefore

$$A_M(x)=\int_{-\infty}^{+\infty}(1-e^{-aMx/(\nu^2+bM^2)})d\nu$$

On defining n and Z as $a_Mx/b_M{}^2$ and ν/b_M respectively, the last integral may be exhibited as

$$A_M(n)=2b_M\left\{\int_0^c(1-e^{-n/(Z^2+1)})dZ+\int_c^\infty(1-e^{-n/(Z^2+1)})dZ\right\}$$

The transformation $y=1/Z$ applied to the second integral of the above makes it possible to write

$$A_M(n)=2b_M\left\{\int_0^c(1-e^{-n/(Z^2+1)})dZ+\int_{1/c}^0(1-e^{-y^2n/(y^2+1)})dy/y^2\right\} \quad (15)$$

The integrals were evaluated graphically by finding the areas under the integrand curves for $n=0.5, 1, 2, 5, 10, 25$. The constant c was taken as 20 (so that an approximation which replaced the second integral by n/c would have been only one percent out of the way).

The resulting plot of A_M against n was very similar to the curve of area as a function of tube-length except for the matter of scale. It was not difficult to apply a process of trial and error to establish values of n and b which secured a good fit of the theoretical A, n curve and the experimental A, x curve. The procedure consisted in studying the ratios of the two ordinates of the A, x curve, for ratios of the x's equal to that between an arbitrary pair of n values and noting when this ordinate ratio was equal to the corresponding ordinate ratio of the A, n curve.

The constants $a_3=1.67\times10^{21}$ and $b_3=1.04\times10^{10}$ were evaluated from the relations $2b_3=A_3(x)/A_3(n)$ and $a_3=b_3{}^2n/x_3$. The integrated absorption coefficient for the line $M=3$ is

$$\alpha_3=\int\mu_3(\nu-\nu_0)d\nu=\pi a_3/b_3=5.02\times10^{11}=16.7\text{cm}^{-1} \quad (16)$$

This is the only absolute absorption coefficient calculated in this way. The deviation of the extrapolation curve obtained by this method from that suggested by the terminated power series expansion method (Method II) was slight and in the expected[19] direction in that the slope at the origin of the former curve was the greater.[20]

Reliability of the Results

The principal sources of inaccuracy in the results given in this paper arise from: (a) experimental uncertainty in taking readings; (b) errors in the base-lines; (c) the cumulative effect of errors which separately may be very small (i.e. use of an inaccurate effective tube-length for the calculations, non-uniformity of the Nernst glower emissivity, uncertainty regarding $\Delta\nu/\Delta\theta$, errors in plotting the data and measuring the areas, etc.); (d) uncertainty regarding the possible effect of selective reflection at the windows of the chamber; (e) errors inherent in the methods employed for calculating the integrated absorption coefficients.

A consideration of the average number of readings and the accuracy of each makes it plausible to assume an accuracy of 0.75 percent for points of the base-line and transmission curves. For gauging the effect of an error of this magnitude on the precision of the measured line areas, it is suggestive

[19] Since the alternating power series was terminated at a positive term and therefore would be expected to give too high values of ω^1.

[20] A fourth method of calculation depended on the assumption of a step like variation for $\mu(\nu)$. The analysis is somewhat involved and is therefore omitted although the value of α_3 calculated in this way is included in Table II.

to treat the absorption line as being of a triangular shape and height k. Considering T_B to be sensibly constant over the line allows us to write

$$\frac{\delta A_M}{A_M} = \frac{\delta T_B}{T_B}\left\{\frac{T_B}{T_B - k}\right\} \tag{17}$$

which reduces to (constant)$\times \delta T_B/T_B$ when it is realized that k/T_B is independent of T_B. Similarly the effect of inaccuracy in the transmission curve may be written

$$\delta A_M/A_M = \delta T^{(x)}/\left[T^{(x)} - k\right] \tag{17.1}$$

These formulas show the importance of using as high values for the base-line transmission as possible. On applying the Fresnel formula for the unavoidable reflection loss at each of the four reflecting surfaces of the two quartz windows, it turns out that in this work the value of the base-line transmission actually attained was only two percent or three percent less than that theoretically possible for infinitely thin windows.

The applications of expressions (17) and (17.1) suggest errors of the order of magnitude of 1 to 8 percent, the lesser values being correlated with the more intense lines in the R branch and the higher values with the weaker lines in this branch and the farther lines in the P branch.

One gauge of the effect due to the non-systematic causes enumerated under (c) would be the difference between the original and the smoothed areas as indicated in Fig. 3C. The smoothing curves are, however, somewhat arbitrary and the fact that the differences are very slight is not to be accepted too easily as a proof of the reliability of the results. However, it is not probable that the error is over 3 or 4 percent for the more accurate lines to 8 or 9 percent in the case of poorer measurements—the correlation being the same as for errors of type (b). The relative values are probably more accurate.

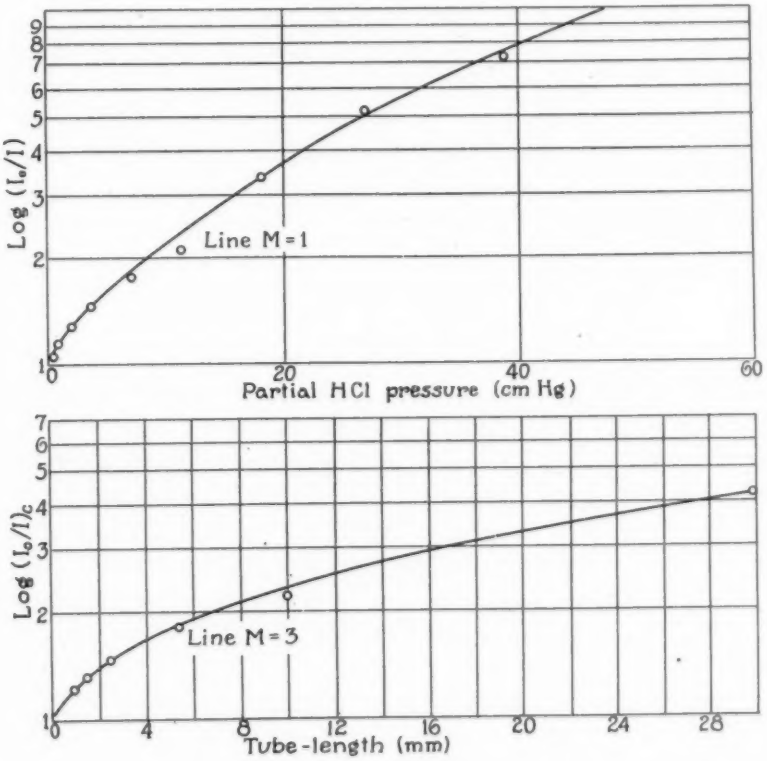
In using Method I an analysis of the error introduced in the final absolute values of the absorption coefficients by the estimated inaccuracies in the areas, indicates that the precision limits are about 15 percent for the stronger lines in the positive branch to about 25 percent for the weaker lines and the lines in the negative branch. The ratio methods are much more reliable especially for the relative values. It appears that a fair estimate for these methods would fix the reliability as being about 10 to 20 percent.

Both the mean square deviation of the calculated points from the best curves in Figs. 3A and 3B and the apparent close check between theory and experiment, to be pointed out later, suggests that the actual accuracy attained is better than these estimates would indicate. The close agreement in the estimates of the absolute value of α_3 as obtained from the four methods of calculating described above lends weight to the reliability of the values of α_M given in Table III.

Discussion of Results

Before entering upon a study of the application of the experimental values of the integrated absorption coefficients to the primary theoretical problem of absorption intensities, it is worth while to remark some important general consequences of the data obtained in this research.

Width of spectral lines and failure of exponential law. One of the striking results is the unexpected magnitude of the absorption for short gas columns as compared with that to be expected from the application of the exponential law to the data for long tube-lengths. The failure of the exponential law for the line $M=3$ is shown by Fig. 6A. The ordinates are the quantities $\log_{10}(I_0/I)_c$ where $(I)_c$ is the apparent intensity of the transmitted light after correction for slit width by the Paschen-Runge[21] formula and the tube-lengths are the abscissas. If the exponential law were obeyed the points in Fig. 6A would lie on a straight line through the point $\log(I_0/I)=1$, $x=0$. The decided curvature is proof that the exponential law is not valid in the region of maximum absorption.



Figs. 6A and 6B. Test of exponential law.

The law fails also when the partial pressure is varied instead of the tube-length, as indicated in Fig. 6B. No slit width correction was applied for

[21] F. Paschen, Ann. d. Physik **60**, 661 (1897).

this case but it is fairly clear that such a small correction would not affect the conclusion.

The apparent failure of the exponential law is due, no doubt, to the fact that the resolving power of the spectrometer with the slit widths used was not sufficient to give the true shape of the absorption curve even when the slit width correction is applied.

The lines are narrower and 'deeper' than they seem. In fact, we can calculate the equivalent half-breadth of the line $M=3$ from the approximating function used in Method III. From Eq. (14) it is readily seen that the half-breadth is $2b_3$. The numerical value is about[22] 2.1×10^{10} frequency units. This is quite small in comparison with the spacing of the lines, which is about 54×10^{10} frequency units in the neighborhood of the line $M=3$. This is the half-breadth of a single line having the same A, x curves as the actual line $M=3$. Since the theoretical separation of the isotopic components is 6.78×10^{10} frequency units, it is clear that the actual half-breadth of the individual components, as calculated by this method, must be less than the equivalent half-breadth of the pair. Moreover, the variation in the isotopic separation with M should have a noticeable effect on the shape of the A, x graphs, as is proved by the curvature of the ratio plots of Figs. 3A and B.

The half-breadth given above is about one-fourth of the lower limit assigned by G. Becker[8] on the basis of his study of the effect of pressure on the HCl band, and about one-fifth of the estimate given by Tolman.[23]

The nature of the absorption curves may be interpreted as follows: Since the absorption lines appear to be really very sharp and quite intense at the center, most of the initial absorption is due to the center of the line and in the case of the strong lines, radiation of frequency corresponding to peak absorption is almost completely absorbed in less than one cm of gas path. For the long tubes the increase in absorption with tube-length is from the less intense absorbing region on either side of the maximum.

The relative intensities of the lines. An immediate conclusion to be drawn from the tabulated values of the integrated absorption coefficients (Table III) is that the intensities in the positive branch are higher than those in the negative branch as required by Eq. (2). Although the single published absorption curve of Brinsmade and Kemble is in agreement with this result the most frequently quoted experimental data (i.e. those of Imes) seemed to belie this prediction of theory.[24]

[22] This estimate depends somewhat on the line shape assumed. A subsequent paper will consider the effect, on the calculated values, of modifications in the supposed line shape and will give the results for the isotopic doublet structure.

[23] R. Tolman, Phys. Rev. **23**, 693 (1924).

[24] Not only are corresponding maxima of Imes' absorption curves distinctly higher for the lines in the negative branch but the intensity estimates derived from these curves by Tolman[23] also emphasize the negative branch. The fact that $\Delta\nu/\Delta\theta$, for a grating decreases with ν indicates one explanation for the appearance of Imes' curves.

Fig. 7 shows a comparison of the experimental results with the formula of Eq. (2). The theoretical points yielded by the two sets of weights $p_M = 1, 3, 5, 7, \cdots$, and $p_M = 2, 4, 6, \cdots$, are both indicated. For the

TABLE III

Tabulated values of the integrated absorption coefficients.

M	Method I $\alpha_M = 46.6 \times 10^{10}$ α_M/α_3 Method I	α_M/α_3 Ratio Methods	Method III 50.2×10^{10} α_M/α_3 Theoretical Values ($p_i = 1,3,5$)	($p_i = 2,4,6$)	Method IV 51.6×10^{10} $\alpha_M \times 10^{10}$ Best Values
1	0.552	0.518	0.474	0.606	25.4
2	0.883	0.857	0.853	0.895	42.
3		1.00	1.00	1.00	49.
4	0.976	0.959	0.961	0.926	47.
5	0.829	0.774	0.782	0.737	37.9
6	0.537	0.542	0.555	0.515	26.8
7	0.310	0.333	0.345	0.316	16.3
8	0.192	0.185	0.189	0.172	9.07
9	0.0847	0.091	0.092	0.083	4.6
10	0.081	0.047	0.040	0.036	2.35
−1	0.479	0.486	0.444	0.570	23.8
−2	0.781	0.764	0.736	0.789	37.5
−3	0.877	0.841	0.840	0.840	41.3
−4	0.79	0.768	0.736	0.731	37.6
−5	0.66	0.604	0.584	0.550	29.7
−6	0.51	0.347	0.389	0.333	21.5

latter sequence only the points calculated from Kemble's theory are plotted since obviously the experimental intensity variations are non-alternating.[25] The agreement is best for the choice of weights[26] $p_M = 1, 3, 5, \cdots$.

The choice of statistical weights may be further tested in two other ways. On the assumption that the general form of Eq. (2) has already been corroborated by the comparison plots of Fig. 7 it appears that the ratio of α_M to the corresponding Boltzman factor $e^{-W_M/kT}$ should yield a quantity proportional to $\bar{p}_M$. The multiplicative factor $|M|/M$ is used in the plot of this ratio against line number (Fig. 8) in order to obtain negative values of this ratio for the lines of the P branch.

The curve obtained is practically a straight line indicating that $\bar{p}_M$ is a linear function of M as expected. The slight curvature is to be ascribed to the influence of the frequency term. A most important characteristic of the curve is that it practically passes through the origin so that $\bar{p}_M$ must be proportional to M. This definitely excludes the series of values $p_M = 2, 4, 6, \cdots$.

For the vibration-rotation bands the summation rule leads to the same type of intensity variation for the choice of weights $p_M = 1, 3, 5, \cdots$, as

[25] Discussion under summation rule.

[26] The new quantum theory by admitting the state $m = 0$ and integral rotational quantum numbers seems to require this choice also.

does Kemble's theory. For other choices however it may easily be verified[15] that alternating intensities are prescribed.[27]

Absolute intensities and transition probabilities. The absolute values of the absorption coefficients are given in Table II. Method I was used to yield absolute values of the coefficients for all lines in the positive branch, while

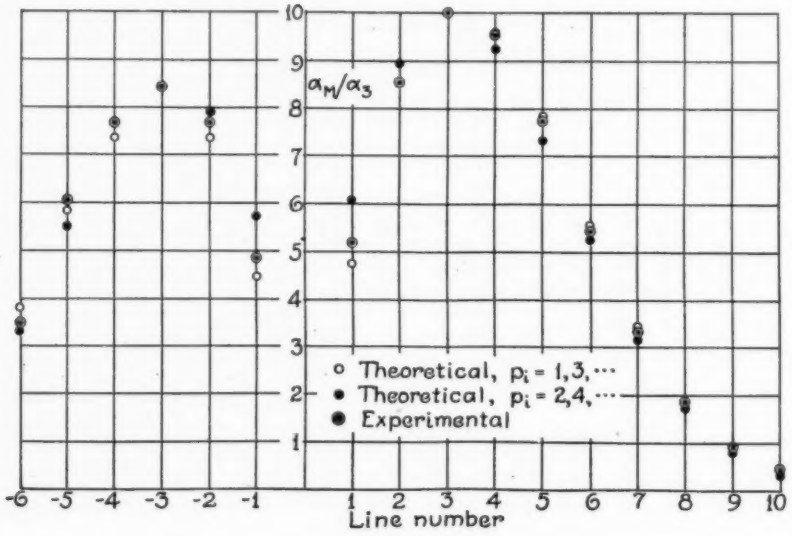


Fig. 7. Comparison of theory and experiment.

the other methods were used for the calculation of the single value for the line $M=3$. The best values of the absolute intensities,[28] namely those in the last column of the table were obtained by using the average value of α_3 as given by the methods listed in conjuction with the relative values derived from the ratio plots.

An important application of the data concerns itself with the Einstein probability-of-transition coefficients. It has often been shown that the integrated coefficient of absorption may be expressed in the form

$$a_M = h\nu_M N_i B_{if}/c \tag{18}$$

where the subscripts i and f refer to the initial and final states, $B_{i,f}$ is the Einstein coefficient of forced transition, ν_M is the frequency associated with

[27] If the HCl lines are unresolved doublets and not singlets as ordinarily supposed, it may be shown that the summation rule replaces $\bar{p}_M$ by the sum $\bar{p}_M+\bar{p}_{M+1}$. The experimental data are therefore also in keeping with the assumption of a doublet line structure with the statistical weight series $p_M=2, 4, 6, \cdots$, since the summation rule predicts the set of $\bar{p}_M$ values $\bar{p}_M=2, 2, 4, 4, \cdots$ with this choice of p_M. Mulliken's work on the correlation of the number of electrons in the molecule and the type of spectroscopic multiplet emitted (or absorbed) suggests a singlet structure in the HCl band spectrum.

[28] Tolman's estimates[22] are based on Imes' curves for a single tube length and are quite out of accord with the present results.

the transition $i \rightarrow f$ and N_i is the number of molecules in the state i. On evaluating N_i there is obtained after inverting formula (18)

$$B_{i,f} = \frac{a_M c e^{W_i/kT} 8\pi I k T}{\nu_M p_i N h} \tag{19}$$

The well known relation between the coefficients of forced and spontaneous transitions may be written

$$A_{f,i} = \frac{8\pi h \nu^3 p_i B_{i,f}}{c^3 p_f} \tag{20}$$

where $A_{f,i}$ is the coefficient of spontaneous transition and the other terms have the meanings attached previously. On combining Eq. (19) and Eq. (20) there results the following expression for calculating $A_{f,i}$ from the data.

$$A_{f,i} = \frac{(8\pi\nu_{i,f})^2 e^{W_i/kT} k I T \alpha_M}{c^2 p_f N h^2}$$

Reference to Eq. (2) shows that neglecting frequency terms, $B_{i,f}$ and $A_{i,f}$ vary as $\bar{p}_M/p_i$. The salient features of the dependence of the coefficients on line number are (a) the comparatively slight difference in value of the coefficients for various lines, (b) the identity of the limiting values of the two types of coefficients for the P and R branches. Conclusion (b) is subject to modification because of neglected frequency terms. $B_{i,f}$ is expected to vary with the inverse 4th power of the frequency and $A_{f,i}$ with the inverse first power.

The values[29] $B_{0,1} = 5.12 \times 10^{15}$ and $A_{0,1} = 58$, associated with the lines $M = 1$ and $M = -1$ respectively, were calculated from formulas (19) and (20.1). The value of $A_{0,1}$ (and the values of $A_{f,i}$ which may readily be calculated from it) are about ten times those of Tolman;[23] however even the values given here are rather smaller than might at first be expected. The low values appear to have given Professor Tolman[30] some concern at the time but are really bona fide and in harmony with the predictions of the correspondence principle, as will appear incidentally in the following discussion of the effective ionic charge.

Since the absolute intensities of the lines are determined by the variation in the electric moment which accompanies the vibration, the amplitude of the electric moment variation can be determined from the absolute absorption coefficients.

[29] The subscripts on the Einstein coefficients refer to the rotational quantum numbers for the states involved.

[30] The wide range of values of $A_{f,i}$; obtained by Tolman is due to his erroneous values for α_M. Several of his conclusions are therefore to be modified and certain of his laws may obviously be made more precise in view of the substantiation of eq. (2).

The electric moment denoted by $p(r)$ differs in value from the product of the nuclear separation and the charge on an electron because of the distortion of the Cl ion's symmetrical electronic configuration due to the presence of the H nucleus. The immediate object of this part of the paper will be to correlate the disturbing effect of the H ion with the distance apart of the nuclei. The calculation will first be carried through on the basis of the older form of quantum theory and as a first step the correspondence principle value for A_{01} is written[31]

$$A_{01}=\frac{16\pi^4\nu_{01}^3}{3hc^3}\,\overline{R}_{01}^2\,\frac{\bar{p}_M}{p_M} \tag{21}$$

where $\overline{R}_{01}^2$ is a certain mean square value of the Fourier series component of the variable electric moment $p(r)$ associated with the transition giving rise to the line $M=-1$.

It may easily be shown that A_{01} is practically equal to the coefficient of spontaneous transition for a linear oscillator and that the effect of the rotational motion is very slight in modifying the value of R as calculated for the vibrational motion alone.

Practically all the usual methods of taking the average of R_{01}^2 for the linear oscillator as required in Eq. (21) lead to nearly the result

$$\overline{R}_{01}^2=\tfrac{1}{2}R_{n=1}^2 \tag{22}$$

$$\text{or} \quad = R_{n=1}^2 \tag{22.1}$$

where the assumption made for (22) is that the zero vibrational state is the initial state whereas the calculation for (22.1) supposes that the state $n=\frac{1}{2}$

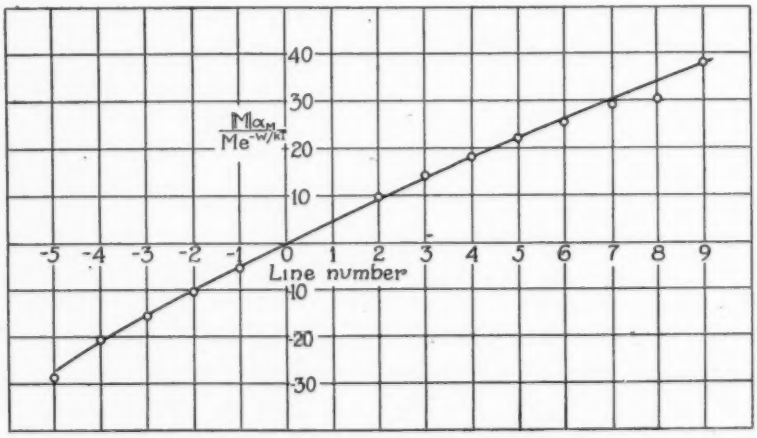


Fig. 8. Test of statistical weight choices.

is the lowest. The new formulation of the quantum theory leads to the relation $\overline{R}_{01}^2=R^2{}_{n=1}$.

[31] Cf. p. 811 for the presence of the factor $\bar{p}_M/p_M=2$.

The analysis of the line spacing and position in the HCl bands yields the value[33] $r_0 = 1.28 \times 10^{-8}$ cm for the equilibrium separation of[32] the nuclei and $\delta = 0.12 r_0$ for the amplitude of vibration about the equilibrium position for one quantum of vibrational energy.

Neglecting the contribution of harmonic terms the value of R_{n-1} is $(dp/dr)_{r=r_0}\delta$. The simultaneous solution of Eqs. (21) and (22) leads to an expression for $(dp(r)/dr)_{r=r_0}$ in terms of known constants. On defining the "effective charge" as $q = p(r)/r$ one may write $(dp/dr)_{r=r_0}$ as $q_0 + (dq/dr)_{r=r_0} r_0$.

Zahn's[33] data for the dielectric constant of HCl yields values of $p(r)$ when substituted into expressions correlating the value of the dielectric constant and electric moment. The assumption that all the dipoles are similar and oriented at random leads to the Debye[34] formula. Pauli[35] and Pauling [36] have treated the problem on the assumption of a space quantization assuming integral and half integral rotational quantum numbers respectively. The new quantum theory reproduces the values of the constants occurring in the classical Debye formula.

At ordinary temperatures nearly all the molecules are in the lowest vibrational state. The Debye equation, or the modifications mentioned, when applied to Zahn's data yield the value $\bar{p}(r) = q_0 r_0$ even if one half quantum of vibrational energy is assumed for the lowest state. It is therefore possible to estimate $(dq/dr)_{r=r_0}$ by combining Zahn's value of $q_0 r_0$ with $(dp(r)/dr)_{r=r_0}$ as calculated in this paper. Table IV contains the values of q_0 and $(dq/dr)_{r=r_0}$ calculated on the basis of the several theoretical variants mentioned.

TABLE IV

Calculation of q_0 and $(dq/dr)_{r=r_0}$

Entries under the headings *N* or *I* are calculated under the assumption of half integral vibrational quantum numbers for the first and integral values for the last.

	Classical and new quantum theory		Pauli theory		Pauling theory	
Apparent charge q_0 (Calculated from C. T. Zahn's data)	0.818×10^{-10}		$.300 \times 10^{-10}$		$.261 \times 10^{-10}$	
	N	*I*	*N*	*I*	*N*	*I*
$(dp(r)/dr)_{r=r_0} \times 10^{10}$	0.828	1.17	0.828	1.17	0.828	1.17
$(dq(r)/dr)_{r=r_0} \times 10^2$	0.008	0.196	0.414	0.679	0.442	0.71
$q_0/r_0 \times 10^2$	0.646	0.646	0.237	0.237	0.206	0.206

With the exception of the classical theory estimates and those depending on the new quantum theory it appears that the ratio $(dq/dr)_{r=r_0} : q_0/r_0$ is greater than 1 (Table IV). If the older form of the quantum theory be adhered to, the inference would be that somewhere near the origin the effective

[32] E. C. Kemble, Jour. Opt. Soc. **12**, 1 (1926).
[33] C. T. Zahn, Phys. Rev. **4**, 400 (1924).
[34] P. Debye, Phys. Zeits. **13**, 97 (1912).
[35] W. Pauli, Zeits. f. Physik **6**, 139 (1921).
[36] L. Pauling, Proc. Nat. Acad. Sci. **12**, 32 (1926).

charge vs. nuclear separation curve is convex to the nuclear separation axis[37] or from another point of view that the formal continuation of the $q(r),r$ curve past the equilibrium point would intersect the $r=0$ axis below the $q(r)=0$ line. Consideration of simple models would suggest a positive value for the ordinate of the intersection point. The results seem, therefore, to be in harmony with the new rather than with the old quantum theory.[38]

The writer wishes to thank Professor Lyman, Professor Pierce and Professor Chaffee for their kindness in placing the facilities of the Jefferson and Cruft Laboratories at his disposal and also to note his appreciation of the helpful advice of members of the Harvard faculty of Physics and Professor Bennett of Lehigh University He is under special obligations to Professor Kemble who interested him in this subject and contributed many valuable suggestions.

JEFFERSON PHYSICAL LABORATORY,
HARVARD UNIVERSITY.
September 21, 1926.

Note added in proof, April 21, 1927.—In the interim since this paper was presented for publication the emphasis in modern physics has changed somewhat; so that references to the new quantum theory are to be interpreted in terms of 'wave' rather than 'matrix' bases. None of the conclusions of this paper are modified by this change in point of view.

[37] Since $q(r)=0$ for $r=0$.

[38] The results are in keeping also with the classical theory or with the assumption that the space orientation predicted by the older quantum theories is incomplete for small fields because of the disturbing influence of molecular collision though the last interpretation in not too plausible.

RELATIVE INTENSITIES OF SOME LINES IN THE MERCURY SPECTRUM

By Joseph Valasek

Abstract

Intensities of the most intense spectrum lines associated with transitions to and from the $2p_2$ state in mercury were measured by means of a photographic method. The spectrum of the vapor was excited by electron impact above the ionization potential. Variations in the line intensities due to changes in the accelerating potentials and vapor pressures were observed. At 22°C and with 50 volt electrons, there were about 1.7×10^{12} quanta of λ2537 radiation emitted per cubic centimeter per second for a current density of 4.75×10^{15} electrons per square centimeter per second. From the intensities of the other lines relative to λ2537, it was found that there are apparently more transitions to $2p_2$ than down from $2p_2$, as given by measurements of the radiation. This made it impossible to determine the probability of excitation of resonance from the intensities of the spectrum lines. A comparison is made between the relative intensities in the experimental tube and in a commercial arc.

THIS work was undertaken for the purpose of obtaining a measurement of the intensities of some of the lines in the mercury spectrum, using different electron speeds and vapor pressures. Lines associated with transitions to and from the $2p_2$ state were chosen with the original intention of obtaining a measure of the excitation of this state. A summary of the technique of line intensity measurements has lately been given by Dorgelo,[1] while the theory of the intensities of spectral lines has been recently discussed by Bartels.[2] In the latter paper it is shown how the intensities of emission lines depend on both the distribution of the various Einstein probabilities of emission and the relative probabilities of excitation of the various states from without the atom. This makes the intensity relations of emission lines difficult to interpret theoretically until one of these sets of probability coefficients is known. However, as suggested by Bartels, one might expect that the probability of excitation of the first resonance level could be obtained by measuring the intensities of lines emitted by transitions to and from this state and comparing the number of transitions to the resonance level with the number obtained from the intensity of the resonance line.

A diagram showing the disposition of the more essential parts in the tube used is given in Fig. 1. The grid G was close to the filament F, so that most of the collisions took place in the space between the grid and the plate P, which were kept at the same potential. The source of electrons was an oxide coating on a platinum surface which was heated by a tungsten filament. The latter was insulated from the platinum except at one end where they

[1] Dorgelo, Phys. Zeits., **26**, 756, (1925).
[2] Bartels, Zeits. f. Physik **37**, 35 (1926).

were connected together. Various accelerating potentials were applied between the platinum sheath and the grid by means of a potentiometer device. The grid and the plate were coated with soot to reduce the number of secondary electrons. The plate current was kept constant at 5 milliamperes throughout the series of observations recorded here. An electric heater wound around the tube made it possible to vary the pressure of the mercury contained inside. The radiation was transmitted to the spectrograph by a re-entrant quartz window Q, 1.28 cm in diameter, and sufficiently off the axis of the cylinder to be out of line with the filament. The window darkened because of a sputtered deposit as the tube was operated, but this effect was corrected for by repeating some of the exposures after a definite interval of time. A sooted nickel surface B, 3.2 cm behind the quartz window, served

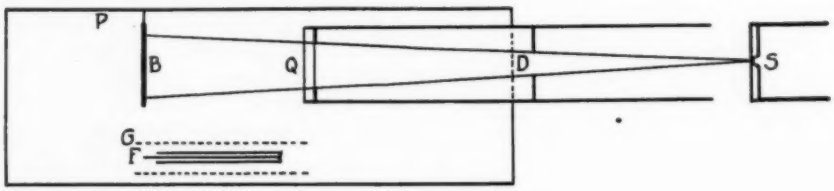


Fig. 1. Diagram of the experimental tube.

as a background. A diaphragm D kept the light reflected from the cylindrical surface from reaching the slit of the spectrograph at S. Since it has been found by R. W. Wood, that mercury vapor even at room temperature absorbs $\lambda 2537$ quite strongly, the room and spectrograph were ventilated, but this did not seem to produce any appreciable change in the results.

Since most of the lines were in the ultra-violet, the intensities of the spectrum lines were measured by a photographic method. The photographic density of each line was measured with a Moll (thermoelectric) microphotometer. The density is defined as the common logarithm of the ratio of the intensity of the light transmitted by an unblackened portion of the plate adjacent to the line, to the intensity of the light transmitted by the blackened portion. In making the exposures, the slit of the spectrograph was made wide enough so that the center of each line was blackened uniformly over a width greater than that of the microphotometer beam. A series of four or five exposures was made for each voltage and temperature. These were for two different times of exposure (either ten and one hundred seconds, or one hundred and one thousand seconds), with and without blackened calibrated wire screens interposed. The transmission factors of the screens used were measured photometrically and also with a Hilger selenium cell. It was assumed that their transmissions were non-selective over the range used.

The relation of the photographic density, D, to the common logarithm of the intensity, $\log I$, is given by the familiar Hurter-Driffield curve, which is straight over a fairly wide range of densities. The straight line is defined by

means of its slope, called the contrast, γ, and the intercept on the log intensity axis which is called the log inertia. The reciprocal of the inertia is called the speed, σ. We have then:

$$\log I = D/\gamma - \log \sigma$$

This formula applies only to the straight region of the characteristic curve, and it is simplest to discard all readings that are too light or too dense to be included in this region. For dim lines, a longer exposure must be given and a different pair of values of γ and σ must be used. Harrison[3] has published values of γ and σ for a number of emulsions for exposures of ten seconds, and for wave-lengths between 4360 and 2144A. From these it is easy empirically to obtain values of these constants for other times of exposure by the use of the calibrated wire screens. Thus no assumption is made regarding the validity of the reciprocity law or of Schwartzchild's law. However, it is best not to rely on these published values too much, for variations may occur in development or in the emulsion itself. Of the two constants, it is the more important to know the value of gamma accurately and it is, fortunately, easy to measure gamma for each plate by the use of a few calibrated wire screens. To obtain $\log \sigma$, on the other hand, is not so easy for its measurement necessitates a set of standard spectrum lines of known intensities. However, if the variation of $\log \sigma$ with wave-length is known, a slight error in its value introduces an error of the same percentage in all the measurements. This will not affect the relative intensities. In calculating the results here presented, Harrison's values of $\log \sigma$ for ten seconds exposure were used, but the values of gamma and $\log \sigma$ for other times of exposure were independently determined for each plate. The plates were developed for five minutes at 21°C in the following developer:

Distilled water	2300 grams	Hydrochinon	12.9 grams
Elon	3.2 "	Potassium bromide	1.84 "
Sodium sulphite	48.7 "	Sodium carbonate	69.0 "

When used, the developer was diluted with three volumes of distilled water to one of developer. The stock solution will keep for several months when kept in a well stoppered bottle.

From the intensities of the lines, one can immediately find how many quanta of each frequency strike the plate per unit area per second. From the light losses in the instrument and the areas of the images and of the slit, one can calculate how many quanta enter the spectrograph per second. Assuming that the fraction of the total number of emissions entering the slit is proportional to the solid angle subtended by the slit, and knowing the portion of the glow which will be within the angular aperture of the instrument, one can calculate the average number of transitions of each kind per cubic centimeter of glow. The factor for converting intensities in quanta per square centimeter of photographic plate to the number of emissions per cubic centimeter of the glow was found to be 2.2×10^3.

[3] Harrison, J.O.S.A. & R.S.I., **11**, 341, (1925).

The relative number of transitions per cubic centimeter per second as compared with the number for λ2537 is plotted in Figs. 2(a) and 2(b) against, respectively, the temperature of the vapor and the accelerating voltage.

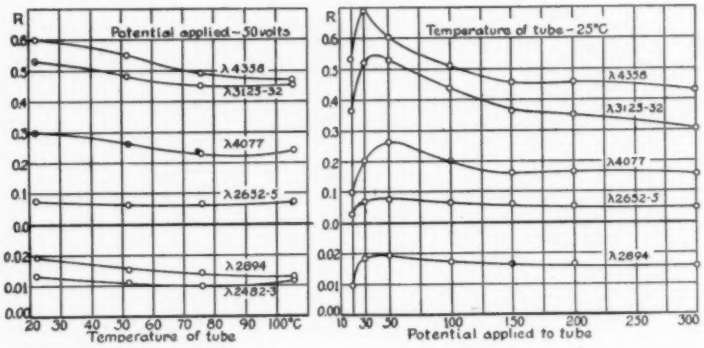


Fig. 2. Numbers of emissions relative to the number for λ2537, (a) Variation with temperature of the vapor; (b) Variation with accelerating potential.

There are no marked changes in the intensities of the lines relative to λ2537 under the conditions of these experiments except at the lower voltages.

The intensity of λ2537 is plotted in Fig. 3 against the same variables. These curves are, of course, not as accurate as those of relative intensities; still they will serve to give the order of magnitude of the intensities and the

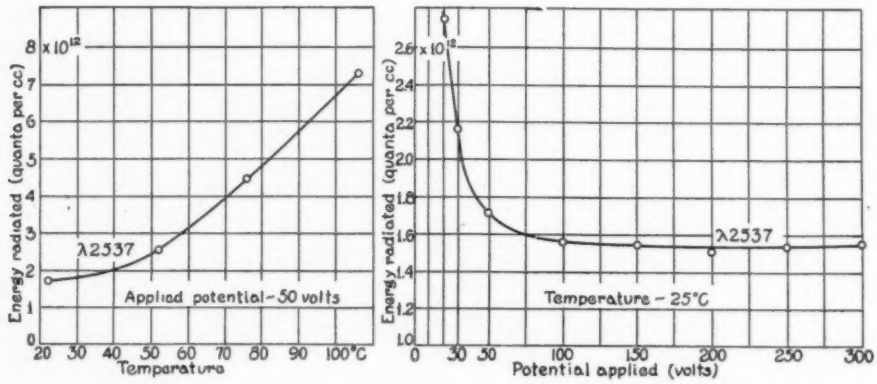


Fig. 3. Number of emissions per cubic centimeter for λ2537, (a) Variation with temperature of the vapor; (b) Variation with accelerating potential.

manner of variation with voltage and temperature. These changes are of the general nature that one would expect. The average current density through the region of the glow photographed was 4.75×10^{15} electrons per square centimeter per second, as measured by a cage having a cross-section equal to that of the glow.

The intensities of the same lines emitted by a commercial "Lab-arc" were also measured. The relative intensities are entirely different from those

in the experimental tube. Table I gives a comparison of these two spectra in terms of the relative number of emissions compared to the number for λ2537.

TABLE I

Comparison of relative number of emissions.

Wave-length	Notation	"Lab-arc"	Exper. Tube 50v.
4358	$2p_2-2s$	8.9	0.60
4078	$2p_2-2S$	0.76	0.30
3126−32 sum	$2p_2-3Dd_{23}$	3.61	0.53
2894	$2p_2-3s$	0.11	0.02
2652−5 sum	$2p_2-4Dd_{23}$	0.91	0.07
2537	$1S-2p_2$	1.00	1.00
2482−3 sum	$2p_2-5Dd_{23}$	0.21	0.01

The data show that there are apparently more transitions to $2p_2$ than from it, at least when one considers only the transitions giving rise to radiation. Therefore it is not possible with either type of source to determine the "external excitation" probability of the $2p_2$ state by taking the difference between the number of transitions from that state and the number to that state as suggested by Bartels. Apparently there are many radiationless transfers down from $2p_2$. The very high current densities in the lab-arc would then be expected to enhance the subordinate series lines as compared with the resonance line.

UNIVERSITY OF MINNESOTA
DEPARTMENT OF PHYSICS
March, 1927.

PROBABILITY OF IONIZATION OF MERCURY VAPOR BY ELECTRON IMPACT

By T. J. Jones*

Abstract

Electrons from a hot filament were projected into an ionization chamber A containing mercury vapor, and were prevented from scattering by a magnetic field of 400 gauss parallel to the electron beam. The positive ions produced in a definite length of A were collected on a plate electrode while the primary electrons after passing through A were collected by a special form of Faraday cylinder. The resulting curve for N, the number of positive charges produced in 1 cm path by an electron moving through the vapor at 1 mm pressure as a function of the electron energy in volts is given. This curve, in good agreement with that obtained by Compton and Van Voorhis for mercury vapor, shows a maximum value of 20.5 at 90 volts. The values of P, the average number of positive charges formed at an impact, were then calculated from N by the relation $P=N\lambda$ where λ is the electronic mean free path. Assuming the kinetic theory value for λ the curve for P shows a maximum value of 0.35 at 90 volts, agreeing well with the value 0.32 at 100 volts calculated similarly by Compton and Van Voorhis. However, when the values of λ obtained by direct experiment are employed, the curve for P shows no indication of reaching a maximum. At 400 volts, P has a value of about 1 and the curve indicates values greater than 1 at higher voltages. Since the probability of ionization at an impact cannot be greater than unity, the assumptions made in evaluating this quantity have been examined more closely.

Such consideration indicates that the assumption that only singly charged ions are produced at an impact is invalid—a view that is supported by the experiments of Smyth. If, as seems reasonable from his experiments, it is assumed that at 400 volts doubly charged and singly charged ions are produced in equal amounts; the present results show that at this voltage the probability of ionization at an impact is about 0.6 while the probabilities of formation of double ions and of single ions are both about 0.3. These results indicate that the values of the probability of ionization at an impact, obtained by former workers for other gases, may also require modification because of the possible formation of multiple ions.

THE probability of ionization in gases by electron impact, as a function of the energy of the impacting electrons, has been examined by a number of investigators[1,2,3] and it has been shown that the probability of an electron's ionizing an atom is not constant but rises from zero when the electron has less than the ionizing energy, to a maximum value when it has some energy higher than the ionizing energy. In all the gases investigated, this maximum value of the probability is less than 0.5 and occurs when the electron energy is equivalent to about 200 volts.

* Commonwealth Fellow.

[1] Hughes and Klein, Phys. Rev. **23** pp. 111, 450, (1924).

[2] W. P. Jesse, Phys. Rev. **26,** p. 208, (1925).

[3] K. T. Compton and C. C. Van Voorhis, Phys. Rev. **26,** p. 436, (1925) and **27,** p. 724 (1926).

K. T. Compton and C. C. Van Voorhis[3] included mercury vapor among the gases examined by them, and found that in this case the probability of ionization at a collision had a maximum value of 0.31 when the electron energy was 100 volts. The subject was deemed of sufficient importance to merit further study by a different experimental method. This paper contains an account of such an investigation on mercury vapor.

Experimental Arrangement and Procedure

The experimental arrangement differed considerably from that of Compton and Van Voorhis. The general method employed was to project a stream of approximately stream of electrons of approximately homogeneous velocity along the axis of a tube into a region devoid of strong electric fields and to collect the electrons and the ions produced by them on a system of electrodes. The electron stream was prevented from scattering by a magnetic field applied parallel to the axis of the tube. Compton and Van Voorhis found that when they tried to use a magnetic field in this way the ratio of the positive ion current I_+ to the electron current I_- was very irregular, being affected by small variations in the magnetic field. As they failed to eliminate or to account for these variations they abandoned the use of the magnetic field. During the course of the present work this effect of the magnetic field was experienced, but after a number of preliminary trials with different experimental arrangements the trouble was found to be due to secondary electrons and was eliminated.

The apparatus employed together with the electrical connections used in making the measurements are shown in Fig. 1. The filament F, consisted of a small loop of tungsten wire just projecting through a small hole (diameter

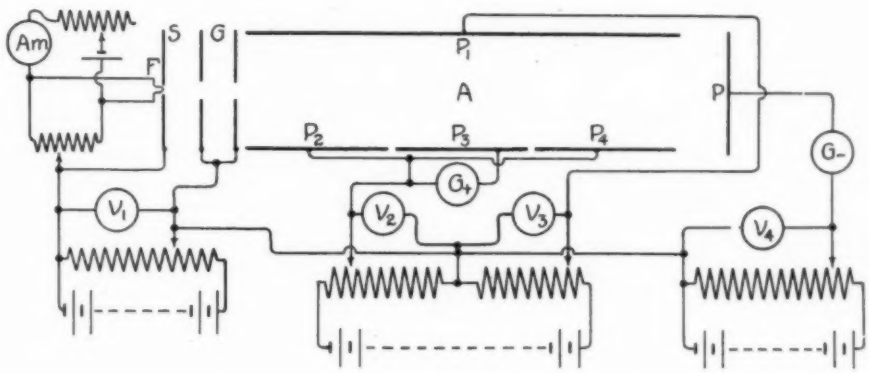


Fig. 1. Diagrammatic sketch of the tube and electrical connections.

2 mm) in the earthed plate S. The middle point of the filament was also earthed by connecting the two ends to a high resistance and earthing an intermediate point. This arrangement served to maintain an almost uniform field V_a between F and the grids G. Electrons from F were accelerated by V_1 through two holes (diameter 4 mm) in the grids into the space A. The

positive ions formed in the region were then collected on the electrodes P_2, P_3, P_4, by applying an electric field between them and P_1. P_2, P_3, and P_4 were separated by thin glass rings. Only the ions formed in the space directly above P_3 are collected on P_3 and pass through the galvanometer G_+ which was used to measure the positive ion current. One reason for adopting this "guard ring" system for the collecting plates was because the holes in the grids G, allowed the accelerating field V_1 to penetrate into the ionization chamber A so that some of the electrons that had passed through the holes would travel some distance in A before attaining their full velocity. Also with this arrangement the positive ions which are measured are produced in a distance traversed by the electrons equal to the length of P_3, i.e. in a region of definite length.

The plates P_2, P_3, P_4 were each 3 cm long and it is reasonable to assume that when the electrons were travelling in the region directly above P_3 they had their full velocity corresponding to V_1. The plate P served to catch the electrons after they had passed through the ionization chamber. Surrounding the electrode system and insulated from it was a copper sheath connected to G which served to eliminate extraneous surface potentials.

All the metal parts, with the exception of the filament, were of copper and were baked out in a small electric furnace at 450°C. At the same time, all the accessible parts were bombarded with an intense electron stream of 1000 volts velocity. The pressure of the mercury vapor was, throughout the experiment, that corresponding to the temperature of the vapor trap between the pumps and the tube. This trap was kept surrounded by melting ice so that the pressure of the vapor in the tube was 0.0002 mm.[4] At such a low pressure it was unnecessary to consider any ionization due to multiple collisions.

The temperature inside the ionization chamber was determined in some of the preliminary experiments by placing a thermometer inside the tube, and was found to be about 70°C. This was taken as the temperature in A throughout the various observations.

The experimental procedure was to measure the positive ion current I_+ and the electron current I_- (by noting G_+ and G_-) as V_1 was increased from zero to 400 volts. The electric field between the collecting plates was meanwhile adjusted so that all the ions formed in A were collected. The magnetic field was also of sufficient strength (usually about 300 gauss) to prevent electrons scattered in the gas from reaching the ion collector. The ratio I_+/I_- gives the number of positive charges produced by each electron in traversing a path 3 cm long in the vapor at a pressure of 0.0002 mm and a temperature of 70°C.

Errors. In the experiments there are several possible sources of error. The main difficulty was that experienced in collecting the electrons after they had passed through the ionization chamber. When a beam of electrons impinges on a metal surface secondary electrons are emitted from that surface. For a given metal the number of these secondary electrons is a func-

[4] A. Smith and A. W. C. Menzies, Ann. d. Physique **33**, 979 (1910).

tion of the velocity with which the primary electrons strike the surface and at the higher-voltages may exceed the number of the primaries. Farnsworth[5] has shown that for copper an appreciable fraction of the secondary electrons have velocities equal to those of the primary electrons. The type of electron collector usually employed is a Faraday cylinder of suitable dimensions. Such a collector was tried without success in the preliminary experiments. A little consideration however, shows that when a magnetic field prevents the electrons from being scattered appreciably, the Faraday cylinder is no longer a complete absorber of electrons.

The arrangement shown in Fig. 1 was tried and it was found that if a suitable electric field V_4 was applied between the ion-collectors and the plate P the number of secondary electrons from P was reduced considerably. For a certain range of values of this field the values of N were almost independent of the strength of the field and this was regarded as an indication that the secondary emission from P under these conditions was small. A further improvement in the arrangement for collecting the electrons was effected by replacing the plate P by a cylinder 14 cm long, closed at one end and having at the other end a hole just large enough to admit the electron stream. Within the cylinder the electrons passed between two copper plates maintained at a potential difference of about 1000 volts. With this arrangement the values of N were quite independent of the strength of the field between the plates when this exceeded a certain value. This could only mean that the cylinder was behaving as a complete absorber of the incoming electrons. The results given in the curves were obtained with this form of collector.

In order to ensure that all the ions formed in A were collected it was found necessary to maintain a potential difference as large as 4 volts between the collecting electrodes. This field could not appreciably affect the motion of the primary electrons as its direction was everywhere perpendicular to that motion. The potentials of the collecting electrodes were always varied in such a way that the potential along the axis of the ionization chamber was the same as that of the accelerating grids, i.e. V_1.

Charging of the collecting electrodes by photo-electric action arising from the incidence of radiation excited in the mercury vapor was prevented by the magnetic field.

The velocity distribution of the primary electrons was not determined but it is reasonable to assume that nearly all of the electrons had velocities close to the velocity corresponding to V_a.

Slow electrons in the primary beam are usually secondary electrons coming from those metal parts, such as grid-wires, which are struck by the primary electrons. The present arrangement of the accelerating grids and the use of the magnetic field enable the electrons to enter A without having struck any metal parts on their way.

[5] Farnsworth, Phys. Rev. **25**, 41 (1925).

Experimental Results and Discussion

The results of the observations are presented in the curves of Figs. 2 and 3. In order to be able to compare them directly with those of Compton and Van Voorhis the ratio I_+/I_- was divided by the pressure in mm and by the length of the electron path in cm. This gives the number of positive charges N which would be produced by each electron in traversing a path 1 cm long in mercury vapor at 1 mm pressure. If one were at liberty to assume, as

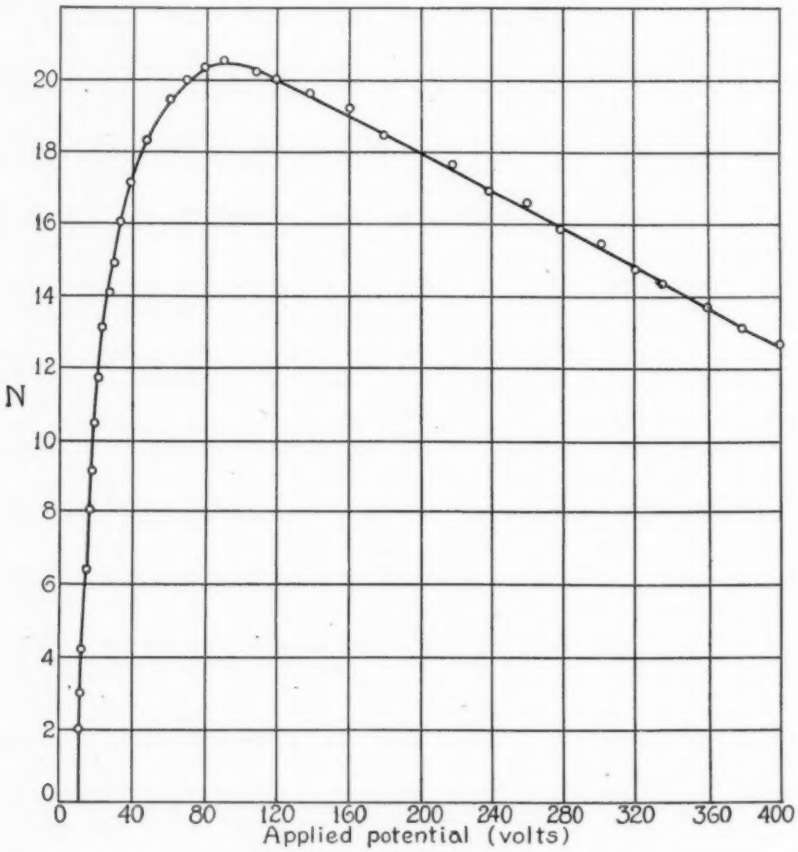


Fig. 2. Curve showing the variation with potential of the number of unit positive charges formed by each electron in traversing one centimeter path in mercury vapor at 1 mm pressure.

has tacitly been done by all other investigators in this field, that the positive ions are all singly charged, N would be equal to the number of positive ions formed by each electron under the above conditions. That the assumption is not justified, particularly at the higher electron velocities, is shown by the observations of Smyth[6] on the formation of multiple ions in mercury vapor and is made further apparent by an analysis of the results of the present experiment. Fig. 2 gives the values obtained for N as a function of the

[6] Smyth, Roy. Soc. Proc. **A102**, 283 (1922).

electron energy in volts. It is seen that N has a maximum value of 20.5 at 90 volts. This value for which N is a maximum together with the voltage at which it occurs agree very well with the values obtained by Compton and Van Voorhis, viz. 21.3 at 100 volts. The temperature of the chamber A was, in their case, 51°C and the difference between that temperature and the temperature in the present experiment is sufficient to account for almost all the difference in the value of the maximum N. After passing its maximum value the curve in Fig. 2 drops almost linearly and more rapidly than in the curve obtained by Compton and Van Voorhis.

If the values of N are divided by the numer of collisions n, made in 1 cm. path by an electron moving through the vapor at 1 mm pressure, the average number P, of positive charges formed per electron impact, is obtained. If the ions were all singly charged P would be the probability of ionization at an impact. The number of collisions, n, is evidently the reciprocal of the electronic mean free path λ, so that $P=N\lambda$. The precise significance of P depends upon the choice of values for λ. If the kinetic theory value of λ is taken, P represents the average number of positive charges formed by each electron when the apsidal distance of its path from the center of an atom is less than the kinetic theory value of the radius of the atom. Compton and Van Voorhis assumed the kinetic theory value of λ in calculating P. The kinetic theory value of λ is $4\sqrt{2}$ times that of the mean free path of the gas molecules and for mercury vapor at a pressure of 1 mm, and at 70°C is 0.0174 cm. The values of P shown in curve 1, Fig. 3, were obtained by multiplying the values of N in Fig. 2 by this kinetic theory values of λ. P is seen to have a maximum value of 0.35 at 90 volts which compares well with the maximum value of 0.32 at 100 volts obtained by Compton and Van Voorhis.

If one takes for λ the values obtained experimentally by Brode[7] and Maxwell,[8] P would represent the average number of positive charges formed by each electron which is deflected appreciably from its rectilinear path. Curve 2, Fig. 3, gives the values of P obtained when Maxwell's values of λ are used. P continues to increase up to the highest voltages and shows no sign of approaching a maximum. At 400 volts P has the value 1 and the curve indicates that at still higher voltages P would have values greater than 1. Brode's values of λ are much greater than those of Maxwell; at 100 volts his value of λ is more than three times as great as the value obtained by Maxwell at that voltage. This would make P greater than 1 even at 100 volts. Maxwell, however, has shown that Brode's values are certainly too large.

Under the assumption that the ions are all singly charged, values of P greater than unity would be meaningless and would throw suspicion on the values of λ used in the calculations. In their determinations of the electronic mean free paths in mercury vapor, Maxwell and Brode consider a collision as a deflection of the electron through an angle greater than

[7] Brode, Roy. Soc. Proc. **A109,** 397 (1925).
[8] Maxwell, Proc. Nat. Ac. Sci. **12,** 509 (1926).

some arbitrary critical angle, whereas in experiments on ionization a collision would be more completely defined as a process in which the colliding electron is deflected from its path or loses energy (possibly without appreciable deflection). Thus the values of λ obtained by these workers may not be appropriate for the evaluation of P. More appropriate values would

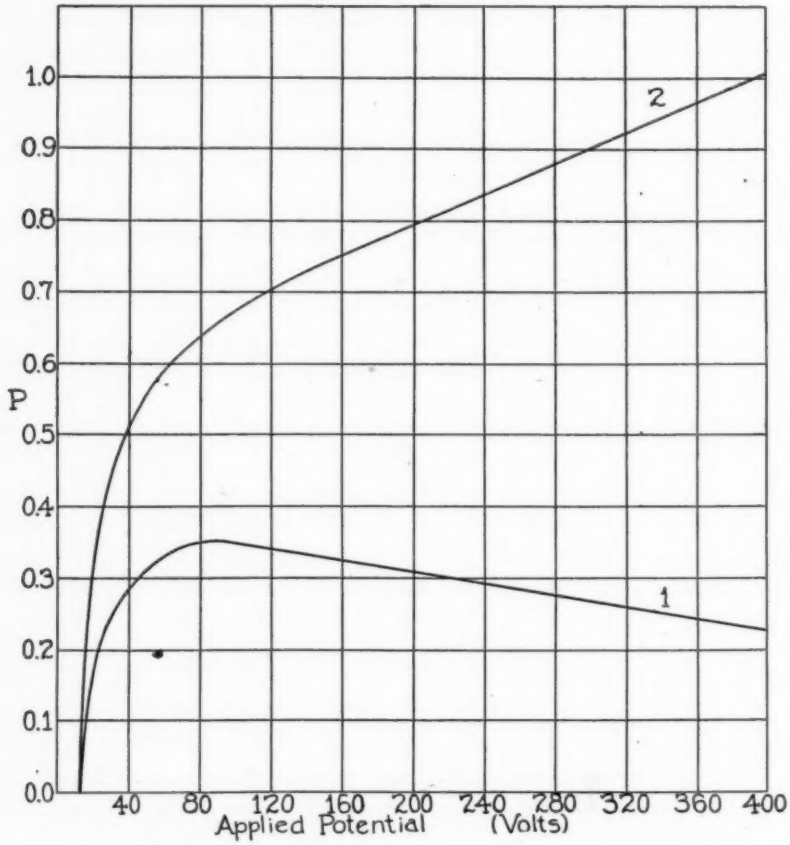


Fig. 3. Curve 1 shows the average number of unit positive charges formed by each electron in traversing a distance equal to the kinetic theory value of its mean free path. Curve 2, shows the average number of unit positive charges formed by each electron in traversing a distance equal to the mean free path as determined by Maxwell.

be those obtained by the method of Ramsauer[9] in which either a deflection or a loss in energy or both is counted as an impact. Unfortunately no measurements by this method have been made for mercury vapor. However, mean free paths which have been obtained by both methods on the same gas indicate that, in the range of velocities used in the present experiment, there is no appreciable difference between them. In other words the chance that an electron loses energy without appreciable deflection is small.

[9] Ramsauer, Jahrb. Rad. u. Elek. **19**, 345 (1923).

It may also be pointed out that if the values of λ in nitrogen and in argon obtained by Brode,[10] using the Ramsauer method, are used to calculate P from the values of N obtained for these gases by Compton and Van Voorhis, P at 325 volts for both argon and nitrogen is about 1.8.

It is therefore probable that the abnormal values of P cannot be accounted for on mean free paths considerations alone. It remains to consider N, the factor other than λ used in calculating P. In regarding P as the probability of ionization at an impact we have assumed that all the ions are singly charged. This assumption, as we have seen, leads to meaningless values of P and consequently we are forced to give up the assumption that all the ions are singly charged.

H. D. Smyth[6] has investigated the formation of multiple ions in mercury vapor. His results show that double ions begin to be formed when the impacting electrons have energies corresponding to 20 volts. At the higher voltages (up to 300 volts) the curves show as many double ions as single and it is believed that the majority of these double ions were produced by single impact. Evidence was also obtained of the formation of triple ions.

If, in the present experiment, it be assumed that only single and double ions are produced and that at the higher voltages these are produced in equal amounts, it is readily seen that the number of positive ions formed by an electron at these voltages would be two-thirds of the corresponding values of N shown in Fig. 2., and the values of the probabilities of ionization in 2, Fig. 3, would be correspondingly decreased. These reduced values of the probability would then be regarded as giving the sum of the probabilities of the formation of single and of double ions, so that at 400 volts the probability of formation of single ions would be about 0.3. It is also probable that the values of P obtained by previous workers for gases other then mercury vapor may also require modification in view of the possible formation of multiple ions. It seems best to postpone any further discussion or speculation suggested by these results until further data are available both on the nature of the collision between electron and atom and also on the formation of multiple ions.

It is a pleasure to acknowledge my indebtedness to Professor John T. Tate who suggested the problem together with the general method of attacking it, and also rendered valuable assistance in overcoming some of the difficulties encountered. The work has been done while the author was a Commonwealth Fellow.

PHYSICS LABORATORY,
UNIVERSITY OF MINNESOTA,
March 30, 1927.

[10] Brode, Phys. Rev. **25**, 5 (1925).

IONIZATION BY COLLISIONS OF THE SECOND KIND IN MIXTURES OF HYDROGEN AND NITROGEN WITH THE RARE GASES

By Gaylord P. Harnwell

Abstract

The effect of the presence of a rare gas in ionized hydrogen and nitrogen was studied by means of a positive ray analysis of the products of ionization. The variation with pressure of the types of ions found was investigated in some detail for both hydrogen and nitrogen in the presence separately of helium, neon and argon. In all of the mixtures studied the evidence tends to support the view that a type of collision of the second kind takes place at which an atom is ionized by colliding with an ion of an atom of higher ionizing potential. Thus at high pressures corresponding to a large number of collisions the equilibrium is displaced in favor of the atom of lower ionizing potential. The following equations can be predicted from a knowledge of the ionizing potentials and they are all supported by the experimental evidence obtained:

$$He^+ + H_2 = He + H_2^+ \qquad He^+ + N_2 = He + N_2^+$$
$$Ne^+ + H_2 = Ne + H_2^+ \qquad Ne^+ + N_2 = Ne + {}^{17}N_2^+$$
$$Ne + {}^{24}N_2^+ = Ne^+ + N_2$$
$$A + H_2^+ = A^+ + H_2 \qquad A + N_2^+ = A^+ + N_2$$

Where ${}^{17}N_2^+$ and ${}^{24}N_2^+$ represent respectively the nitrogen ions produced at the expense of seventeen and twenty-four volts.

The situation for nitrogen is seen to be more complicated than that for hydrogen. In the latter case the evidence shows that the equations listed above are in the order of increasing probability. This tends to support the view that the probability of the transfer's occurring is an inverse function of the difference in ionizing potentials. The phenomena can not be interpreted as accurately in the case of nitrogen. However, the formation of ${}^{24}N_2^+$ by Ne^+ (24.5) was found to be the most probable of all the processes occurring in nitrogen and the results obtained with the other rare gases as far as they can be interpreted are also in accord with this view.

THE work forming the substance of this paper is a continuation of an investigation undertaken to detect any evidence for ionization at collisions of the second kind in mixtures of the rare gases.[1] A very short résumé of the previous results and the mechanism suggested to account for them will serve as an introduction to the rather more complicated situations found to exist in mixtures of the rare gases with hydrogen and nitrogen. The positive ray apparatus was the same as that used in the previous experiments. It was described in detail in the paper cited, so here it will be necessary only to outline the method of investigation employed.

In a partially ionized mixture of two monatomic gases there will be three general types of collisions taking place: atoms will collide with atoms, atoms will collide with ions, and ions will collide with ions. The second type of collision may be divided into two classes: an ion may collide with an atom

[1] Gaylord P. Harnwell, Phys. Rev. **29**, 683 (May 1927).

of higher ionizing potential, or an ion may collide with an atom of lower ionizing potential. In the latter case the ion has a greater electron affinity than the atom and there may be a certain probability of an electron being transferred from the atom of small electron affinity to the ion of the atom of large electron affinity. As this interchange would not be reversible the effect of a large number of collisions would be to increase the number of ions of lower ionizing potential at the expense of those of higher ionizing potential. As the number of collisions would be proportional to the pressure, if a curve representing the ratio of the ion of higher ionizing potential to the ion of lower ionizing potential were plotted against the pressure it should commence to drop at a pressure at which the mean free path of an ion was comparable to the dimensions of the apparatus and continue to fall as higher pressures were reached. Also the slope of the curve should be a measure of the probability of the electron transfer outlined above. Mixtures of helium and neon, neon and argon, and of helium and argon were investigated for evidence of this effect and the following equations, given in the order of their probability, account for the results obtained:

$$\begin{aligned} He^+ + Ne &= He + Ne^+ \\ Ne^+ + A &= Ne + A^+ \\ He^+ + A &= He + A^+ \end{aligned}$$

Considering these equations from the point of view of the ionizing potentials of the gases it will be seen that the interchange is most probable in the case of helium and neon where the discrepancy between the ionizing potentials is least and least probable in the case of helium and argon whose ionizing potentials are the most widely separated. This is of particular interest by analogy with the thermodynamic argument developed by Klein and Rosseland[2] for collisions of the second kind between atoms and electrons where it is shown that the probability of an energy transfer is greatest when the energy to be transferred is least. The argument as there given is not absolutely conclusive nor is it strictly applicable to the present conditions but it is of interest in the light of the above results. One further point should be mentioned, namely that the probabilities of ionization of these rare gases as deduced from the experimental curves were in good agreement with the values obtained by K. T. Compton and C. C. Van Voorhis.[3]

As has been mentioned the apparatus was described in detail in a previous paper.[1] The ions were produced by the usual method of electron bombardment in a region whose pressure could be varied and then drawn into a region of very low pressure and analyzed by a magnetic field. The ion stream was detected by an electrometer and the current taken as a measure of the number of ions of that particular mass emerging from the high pressure region. The analyzing runs were made by varying the accelerating voltage (E_4) for the positive ions. The areas under the peaks obtained by such a run, and plotted on a mass scale ($1/E_4$), were taken as representing the number

[2] O. Klein and S. Rosseland, Zeits. f. Physik **4**, 46 (1921); also Franck, Anregung von Quantensprüngen durch Stösse, Page 210 et seq.

[3] Compton and Van Voorhis, Phys. Rev. **27**, 74 (June 1926).

of ions of the particular type present in the high pressure region. The variation of this quantity with the pressure existing in the ionizing chamber, as measured by a McLeod Gauge as close to the apparatus as possible, was the relation investigated. As the pressure was increased the area under a peak, when a pure rare gas was in the chamber, increased up to a certain pressure due to the actual increase in the number of ions produced and then decreased showing that some of the ions produced were being scattered from the beam before they could emerge from the high pressure region. Consequently at high pressures the ions reaching the electrometer were mainly those produced near the slit which separated the high from the low pressure regions. At sufficiently high pressures the electrons were not able to ionize close enough to the slit so that any of the positive ions could be drawn out and the area under the peak reduced to zero.

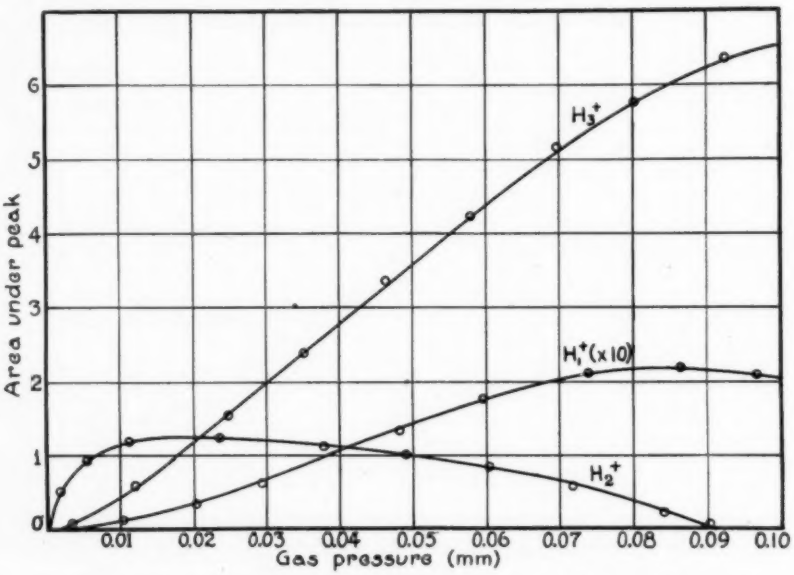


Fig. 1. Effect of pressure on the nature of the positive ion in hydrogen.

In dealing with a diatomic gas the observed phenomena become more complicated as can be seen from Figs. 1 and 2. It is quite well established from the work of H. D. Smyth[4] and of Hogness and Lunn[5] in hydrogen and nitrogen that the primary product of ionization is the molecular ion and that such ions as N_1^+ and H_3^+ are formed as a result of a secondary process. Any ionized hydrogen molecule apparently can dissociate, but the case is slightly different for nitrogen. Hogness and Lunn[5] have shown that two types of N_2^+ exist one having been produced at the expense of twenty-four volts of energy and the other at the expense of seventeen. The former $^{24}N_2^+$ is capable of dissociating into N_1^+ but the latter, $^{17}N_2^+$, is not. Also there

[4] H. D. Smith, Phys. Rev. **25**, 452 (April 1925).

[5] Hogness and Lunn, Phys. Rev. **26**, 44 (1925); **26**, 786 (1925).

is very good evidence for believing that H_3^+ is a secondary and not a tertiary product, that is, that the majority of it is produced directly from H_2^+, and not by way of H_1^+. The above reactions are represented by these equations:

$$H_2 + H_2^+ = H_3^+ + H_1$$
$$H_2^+ = H_1 + H_1^+$$
$$^{24}N_2^+ = N_1 + N_1^+$$

These equations are well illustrated by Figs. 1 and 2. The primary product would be expected to predominate at low pressures where collisions are very infrequent and to behave in that region very much like a rare gas peak. This is what is observed, the primary product rising sharply from the origin. However, as soon as the pressure reaches a value such that an appreciable number of the ions collide before emerging from the high pressure region the character of the phenomena changes. It no longer resembles the

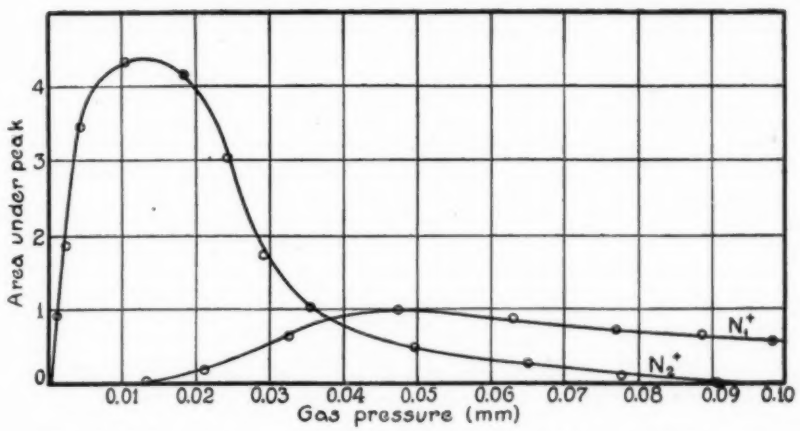


Fig. 2. Effect of pressure on the nature of the positive ion in nitrogen.

rare gas case for the secondary products appear in large quantities and the primary products drop very rapidly. At sufficiently high pressures the primary product entirely disappears though the secondary products are still present. This means that the primary product is only formed in the region so far removed from the slit from which the ions are drawn that it can not reach it without making several collisions at each of which it is likely to be deflected or dissociated. The secondary products on the other hand are formed nearer the slit at one of these collisions and continue toward the slit. There is less chance of their being deflected from the beam, and they are more stable so that there is also less chance of their being dissociated. These phenomena are very evident in both hydrogen and nitrogen. There are two secondary products in hydrogen, H_1^+ and H_3^+, the latter greatly predominated under the conditions which existed in the ionization chamber. The accelerating potential for the ionizing electrons was well above twenty-four volts so in the case of nitrogen N_1^+ is present. When the electrons had only had twenty volts of energy the N_2^+ peak behaved exactly as a rare gas peak and no N_1^+ was observed.

In obtaining the curves of Figs. 1 and 2 and in all that follow the ionizing electrons have fallen through fifty volts, the field drawing the positive ions out of the high pressure region is four volts per centimeter, and the length of this region is about two and a half centimeters. The abscissas in all but Figs. 7, 8 and 9 represent total pressure, and in curves representing the characteristics of mixtures the observed pressure has been multiplied by

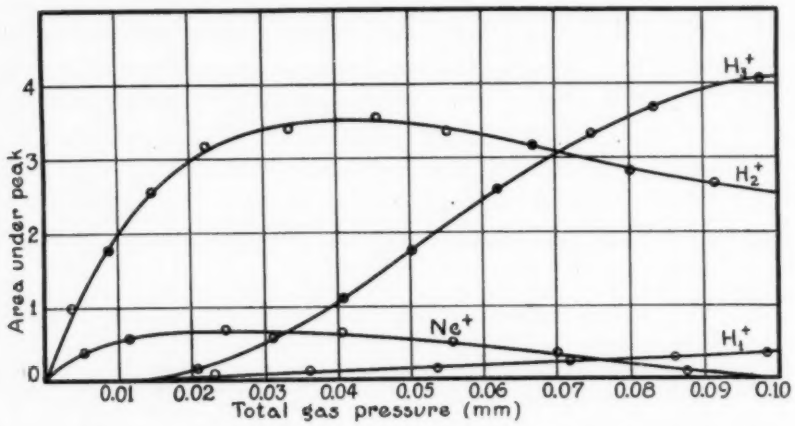


Fig. 3. Effect of pressure on the nature of the positive ion in mixtures of hydrogen and neon.

the ratio of the mean free path in the pure diatomic gas to the mean free path in the mixture so that the abscissae are directly proportional to the number of collisions and the curves are comparable with one another. Also all results refer to mixtures in which the two constituents are present in equal proportions unless otherwise stated.

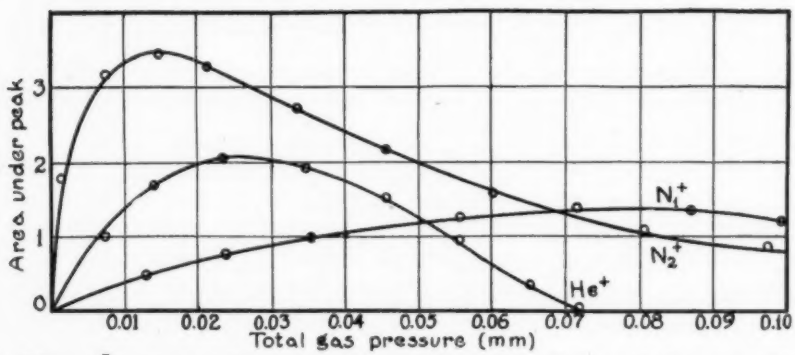


Fig. 4. Effect of pressure on the nature of the positive ion in mixtures of nitrogen and helium.

Figs. 3, 4, 5, and 6 represent the results obtained with mixtures of hydrogen and neon, nitrogen and helium, nitrogen and neon, and nitrogen and argon. The curves obtained with hydrogen and helium and with hydrogen and argon are not reproduced here as the same general phenomena are observed in the analogous curves with nitrogen. The ordinates of all these curves as directly calculated from the experimental data represent the

amount of the particular ion that is drawn out of the region of high pressure in the ionization chamber. In the cases of the curves representing the rare gases in the mixtures these ordinates have been too large to be represented on these diagrams. Hence they have been reduced in such a proportion that they bear the same ratio to the ordinates of the primary product of ionization

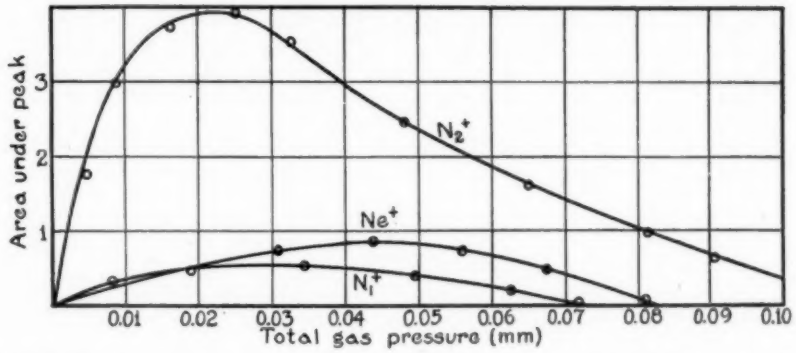


Fig. 5. Effect of pressure on the nature of the positive ion in mixtures of nitrogen and neon.

in the diatomic gas at low pressures as the probabilities of ionization of the two gases as given by the work of Compton and Van Voorhis.[3] The justification for this procedure is that the ordinates of the curves obtained in mixtures of the rare gases with one another were about in proportion to their probabilities of ionization, at low pressures. And the curves obtained by plotting the value of the electrometer current do not represent the ions produced

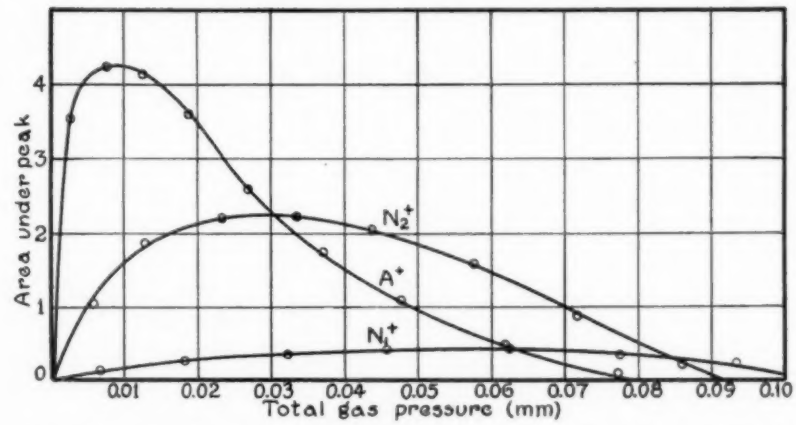


Fig. 6. Effect of pressure on the nature of the positive ion in mixtures of nitrogen and argon.

but only those which pass through the high pressure region. Hence the natural assumption is that the monatomic and diatomic ions are produced in the proportions found by Compton and Van Voorhis but that the probability of a monatomic ion passing through the high pressure region and remaining in the beam so that it will be recorded by the electrometer is

greater than for a diatomic ion. There is other evidence that this is the correct explanation, particularly that obtained from the position of the maximum of the rare gas curve, for the shape of the curve is a function of the probability of ionization and also of the probability of deflection or neutralization. From a consideration of the shapes of these curves in hydrogen and nitrogen it can be seen that the probability of deflection is less in hydrogen than in nitrogen, as would be expected. However, in the following analysis of these curves the rare gas curves are less important than the curves representing the primary and secondary products of ionization in the diatomic gas.

The ionization potentials of the gases used are approximately as follows:

He = 24.5 volts	H_2 = 16 volts
Ne = 21.5	N_2 = 17 and 24
A = 15	

And if the interchange of an electron at a collision between an atom and an ion is completely determined by the electron affinities or ionizing potentials involved it would be expected that the processes taking place would be represented by the following equations; where N_2^+ represents both types of ion:

$He^+ + H_2 = H_2^+ + He$	$He^+ + N_2 = N_2^+ + He$
$Ne^+ + H_2 = H_2^+ + Ne$	$Ne^+ + N_2 = {}^{17}N_2^+ + Ne$
	$^{24}N_2^+ + Ne = Ne^+ + N_2$
$A + H_2^+ = H_2 + A^+$	$A + N_2^+ = N_2 + A^+$

Where the type of N_2 ion is not specified either one can be considered as obeying the equation. Also, if the relation that the probability of a transfer is inversely proportional to the amount of energy in excess of that transferred is found to be as applicable in the case of diatomic as in the case of purely monatomic mixtures, it would be expected that the hydrogen equations as listed are in the order of increasing probability. The nitrogen equations represent a more complicated case and it is a little difficult to know just how the probabilities should run except that the first equation should be the most probable, on these simple assumptions, as the difference in ionizing potentials for $^{24}N_2$ and Ne is only of the order of half a volt.

The phenomena observed in the mixtures containing hydrogen will be considered first and for the purpose of simplifying the discussion a slightly different method of plotting will be employed. The abscissas again represent the pressure, in this case the partial pressure of hydrogen, and the values are corrected for the difference of free path in the various mixtures so that they are really proportional to the number of collisions. The ordinates represent the value of the ratio H_2^+/H_3^+, this is the ratio of the primary to the secondary product of ionization. The ratio $H_2^+/H_1^+ + H_3^+$ could be used, but H_1^+ was present in such small quantities that the difference between these two ratios would be inside the limit of accuracy of the experiment. It brings out in a very convenient way the processes taking place, for the only difference in the conditions under which the curves shown in Fig. 7 are obtained is in

the type of collision possible to the two members of the ratio, that is whether the hydrogen can collide just with hydrogen or also with helium, neon, or argon. There will not be the possibility of the formation of H_3^+ at a rare gas collision for it can only be formed at a collision with another H_2 particle, hence the increased value of the ratio at high pressures in the mixtures will represent the secondary production of H_2^+.

The curve marked 1 in Fig. 7 represents this ratio under normal conditions when only hydrogen is present. The curve drops from a very high

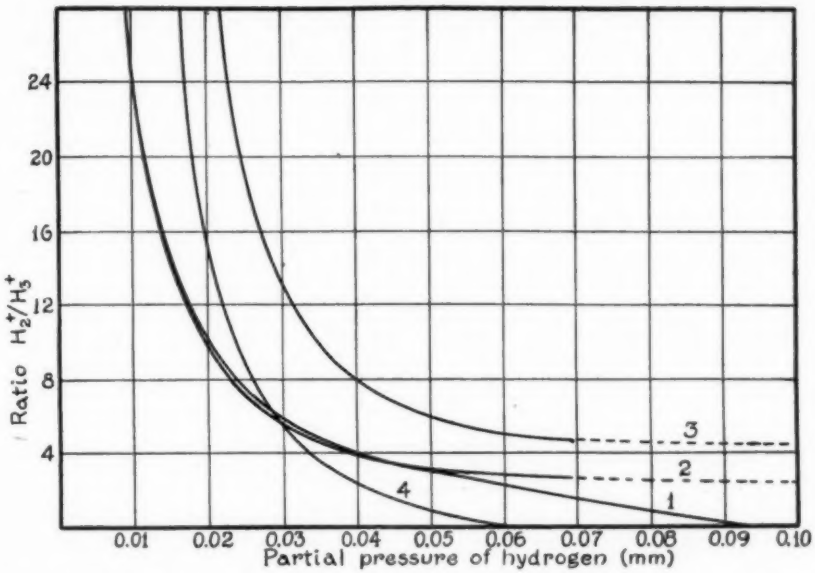


Fig. 7. Ratio of H_2^+/H_3^+ as a function of the partial pressure of hydrogen. Curve 1, in pure hydrogen; curve 2, in the presence of helium; curve 3, in the presence of neon; curve 4, in the presence of argon.

value at low pressures to zero at about nine hundredths of a millimeter. The reason that H_2^+ disappears is, as we have seen, that at that pressure the electrons from the filament are no longer able to ionize the hydrogen close enough to the low pressure region so that an appreciable amount of the ionized product can be drawn out without having suffered any collisions. H_3^+ being the secondary product and capable of surviving many collisions does not even reach its maximum value till after the H_2^+ has completely disappeared.

The curve marked 2 represents the variation of this ratio with pressure when helium is present in the ionization chamber. The character of this curve is quite different for pressures above five hundredths of a millimeter. Above that pressure as far as experimental points could be obtained the ratio H_2^+/H_3^+ remains practically constant. The interpretation of this is that H_2^+ is being produced near enough to the slit so that it can emerge from the high pressure region without having been dissociated. As we have seen, electrons are not able to do this, hence these hydrogen ions must have been

produced by collisions with helium ions. There is the alternative possibility that they may have been produced by collisions with excited helium atoms. In the present apparatus the two possibilities can not be distinguished. However, as the life of an ion would be much longer than that of an excited atom the first explanation is much the more likely. The process occurring can be represented by the equation:

$$He^+ + H_2 = H_2^+ + He$$

The curve marked 3 represents the behavior of the ratio in the presence of neon. It is evident that the effect of neon is very similar to that of helium. The fact that this curve does not coincide with curves 1 and 2 at low pressures probably has little significance. It would be amply accounted for if the probability of deflection of an ion depended on the type of particle with which it collided. This is certainly very probable and it has not been previously allowed for. The chief difference between curves 2 and 3 is that the high pressure value of the ratio is considerably greater in the latter case. That is more H_2^+ is produced in neon than in helium for the same number of collisions. The equation would be similar to the helium one:

$$Ne^+ + H_2 = H_2^+ + Ne$$

The curve marked 4 represents the behavior of the ratio in the presence of argon. The shape of this curve differs greatly from that of the two preceding ones. It would appear that a reverse phenomenon is taking place. The two possibilities to account for a change in the ratio are: that H_3^+ is created at a collision with an argon particle or that H_2^+ is destroyed. The former is obviously impossible directly and probably may be entirely neglected. The latter is exactly what would be predicted by the argon hydrogen equation:

$$A + H_2^+ = A^+ + H_2$$

It is difficult to form an accurate idea of the probabilities of electron interchanges between hydrogen and the rare gases from Fig. 7. However, the ordinates of curves 2 and 3 at high pressures tend to show that the process associated with 3 is the more probable. The hydrogen curves analogous to Figs. 4 and 5, which are not reproduced here, bring this out much more clearly and also tend to show that the process associated with 4 is the most probable of all. This is exactly what would have been expected by analogy with the rare gas mixtures[1] as can be seen by referring to the ionizing potentials given above.

Fig. 8 gives the analogous curves for nitrogen. The ordinates represent the values of the ratio N_2^+/N_1^+, and the abscissas are the partial pressures of nitrogen. These curves are very similar to those in Fig. 7 except that curve 3 representing the ratio in the presence of neon is missing. By referring to Fig. 5 it can be seen that the ratio has an infinite value in that pressure range where the other curves are of the most interest. The neon case will be discussed separately. In this case also the fact that the curves do not coincide at low pressures is probably not of great significance due to the considerations mentioned while discussing Fig 7.

The curve marked 1 representing the ratio in pure nitrogen is very similar to the analogous curve in the case of hydrogen. Its behavior is almost identical throughout the entire pressure range. In this case also of course the ordinates represent the ratio of primary to secondary product, but the type of secondary product concerned is very dissimilar and Figs. 1 and 2 bear little resemblance to one another, hence it is rather remarkable that curves 1 in Figs. 7 and 8 should be so very much alike.

Curve 2 represents the ratio in the presence of helium. It is apparent that its behavior is very similar to the analogous curve in the case of hydrogen. The only differences are that the slope decreases more rapidly in the low pressure region of the curve and that the values of the ordinates approached almost asymptotically at high pressures are considerably greater

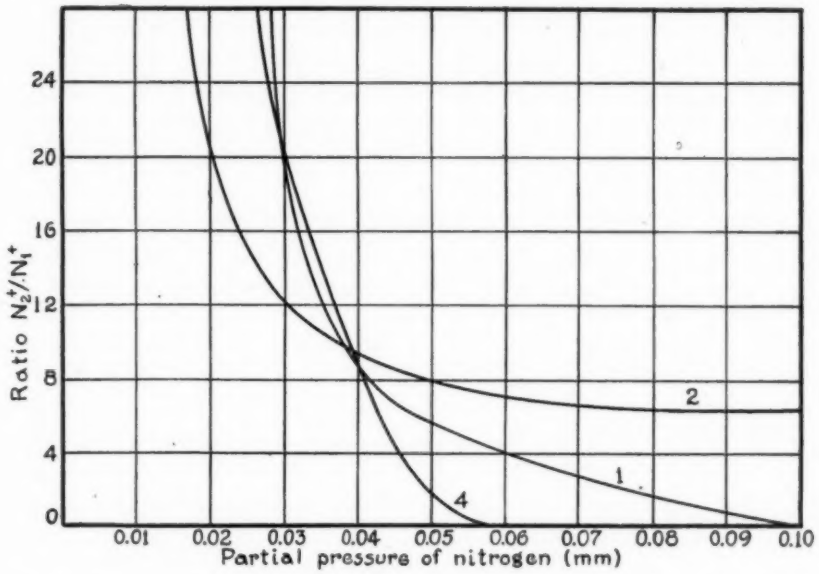


Fig. 8. Ratio of N_2^+/N_1^+ as a function of the partial pressure of nitrogen. Curve 1, in pure nitrogen; curve 2, in the presence of helium; curve 4, in the presence of argon.

than those of curve 2 in Fig. 7. These differences are such as to be most easily accounted for by assuming a larger value for the probability of ionization of a nitrogen molecule when it collides with a helium ion than for the probability of ionization of a hydrogen molecule at a similar collision. This is in a general way what would be predicted from the ionizing potentials if it is true that the transfer is more likely when the energy to be transferred is smaller. The difference, however, should be very small for $^{17}N_2^+$ but very large for $^{24}N_2^+$. The equation representing the transfer would be analogous to the hydrogen one:

$$He^+ + N_2 = N_2^+ + He$$

The phenomena, however, are rather more complicated in the case of nitrogen. In the first place the secondary product entering into the radio

plotted in Fig. 7 can not be increased at collisions between H_2^+ and the rare gas particles. This is not true in the case of nitrogen. For N_1^+ can be formed at any collision of $^{24}N_2^+$, if indeed a collision is necessary at all. In the second place two types of primary product are possible in the case of nitrogen, namely: $^{24}N_2^+$ and $^{17}N_2^+$. The former can dissociate at a collision, or possibly spontaneously, into N_1^+. However, without more accurate knowledge of the probability of formation of the two types of primary product and of the probability of dissociation of $^{24}N_2^+$ only qualitative interpretations of the data that have been obtained are possible. The quantity of N_1^+ observed is probably a measure of the amount of $^{24}N_2^+$ present but the details of the dissociation such as the necessary conditions and probability of occurrence are not known. Hence the curves in Fig. 8 represent a more complicated situation than those in Fig. 7, and the main interest in this method of plotting is in the possibility of comparison between the two figures. Considering curve 2 of Fig. 8 in more detail it is seen that the numerator of the ratio can be increased by an increase in either primary product but that the production of one of these also automatically increases the denominator, hence it would be difficult without accurate knowledge of the probabilities involved to predict the form curve 2 would take. More information is given, however, by Fig. 4, which represents the variation of the ions with pressure in a mixture of nitrogen and helium. From this figure it can be seen that both N_1^+ and N_2^+ exist in larger quantities at high pressures than in pure nitrogen. this is what would be expected if they are produced at collisions with helium ions. The fact that a large amount of N_1^+ is observed at high pressures is very significant for it shows that a very large proportion of the nitrogen ions produced by the helium ions are of the type $^{24}N_2^+$. This is interesting from at least two points of view. In the first place it definitely places this ionization potential of nitrogen below the ionization potential of helium. In the second place it shows that the first of the following equations is much more probable than the second:

$$He^+ + N_2 = {}^{24}N_2^+ + He$$
$$He^+ + N_2 = {}^{17}N_2^+ + He$$

This is of interest from the point of view of the energy interchange occurring.

Curve 4 in Fig. 8 representing the variation of the ratio with pressure in the presence of argon is of some interest by comparison with the analogous curve in Fig. 7. The forms of the two curves are very similar, the outstanding difference being that the decrease is more rapid for the nitrogen ratio. This is exactly what would be expected from the foregoing considerations. N_2^+ would be decreased in accordance with the equations:

$$A + {}^{24}N_2^+ = A^+ + N_2$$
$$A + {}^{17}N_2^+ = A^+ + N_2$$

The latter being by far the more probable. Also N_1^+ would be increased by the collisions between $^{24}N_2^+$ and A^+ and also probably at a certain number of collisions with neutral argon; in fact, the validity of the first equation is rather doubtful. It is difficult to obtain much more information from Fig. 6.

However, it can be seen by a comparison of Figs. 2 and 6 that the rate of decrease of N_2^+ is much more rapid at high pressures when argon is present (all pressures given are total pressures) than in pure nitrogen. This is less true for N_1^+. If of any significance at all this may be taken as supporting the second rather than the first equation just given.

Fig. 5 represents the results obtained in a mixture of nitrogen and neon. The most striking difference between it and Figs. 4 and 6 is seen to be the behavior of the N_1^+ ion. The secondary product of ionization actually disappears before the primary one. This has not been true in any of the preceding mixtures. The cause of this is probably contained in the equations:

$$Ne^+ + N_2 = {}^{17}N_2^+ + Ne$$
$$Ne + {}^{24}N_2^+ = Ne^+ + N_2$$

According to these equations the only N_2^+ ion formed by a collision of the second kind with a neon ion is the type of ion not capable of dissociation. Hence at high pressures the only ions produced near enough to the analyzing chamber to be able to emerge from the high pressure region and be detected are N_2^+ ions. This was not true in the case of the helium mixture for in that case the $^{24}N_2^+$ was produced in large quantities and it could dissociate giving N_1^+. In addition to this effect the presence of neon according to the second equation tends to decrease N_1^+ by decreasing $^{24}N_2^+$. These are exactly the phenomena which are observed. The N_1^+ ion decreases more rapidly than in any other mixture and disappears at a comparatively low pressure. On the other hand the N_2^+ ion is apparently little effected by the presence of

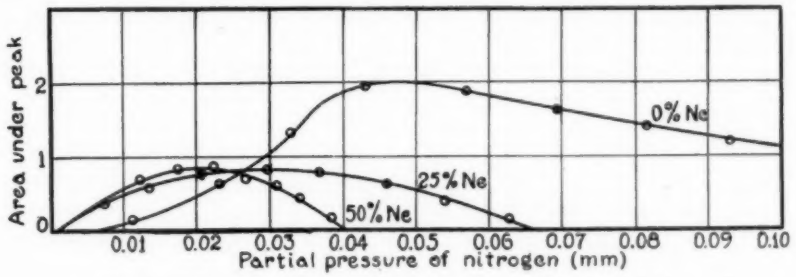


Fig. 9. Effect of mixtures of neon on the number of N_1^+ ions.

neon. Making the proper change in abscissae N_2^+ behaves much as it does in pure nitrogen. The effect of neon is about half way between that of helium and that of argon. This is just what would be expected from the equations for N_2^+ is increased at one type of collision and decreased at the other. Little can be said of the relative probabilities of these processes except that they must be of the same order of magnitude and probably roughly equal. From a consideration of Figs. 4, 5, and 6 it can be seen that by far the most probable of these ionizing processes that we have been considering is the production of $^{24}N_2^+$ by He^+. The difference in ionizing potentials in that case is of the order of half a volt.

Fig. 9 has been included to show the very striking way in which N_1^+ decreases in the presence of neon. The ordinates represent the area of the

N_1^+ peak and the abscissa are the partial pressures of the nitrogen. N_1^+ is greatly decreased in the presence of 25 percent neon and still further when the neon is increased to 50 percent. This is exactly the result predicted by the second equation. If a sufficient number of collisions occurred the two equations could be considered together:

$$Ne + {}^{24}N_2^+ = Ne + {}^{17}N_2^+$$

Thus it can be seen that the equilibrium at high pressures would be displaced greatly in favor of the stable form of N_2^+. It might also be mentioned that the N_1 ionizing potential though not known accurately is certainly below that of Ne and reactions involving N_1 may be completely neglected.

Conclusions

From the detailed and rather complicated analysis of the experimental results two main conclusions become evident. The first is that at a certain number of collisions between an atomic or a molecular ion and an atom or ion of lower ionizing potential an electron transfer will occur. In all the mixtures of gases that have been studied so far no exception to this has been observed. The processes expected to occur at a collision can be predicted from a knowledge of the ionizing potentials of the atoms or molecules involved. Secondly the probability that a given transfer will occur appears to be an inverse function of the difference between the ionizing potentials involved. By far the most probable transfers seem to be those in which the ionizing potentials of the two gases concerned are nearly equal. When there is a large amount of excess energy the probability of the process occurring is very much smaller.

In conclusion I want to express my deep gratitude to Professor K. T. Compton and Professor H. D. Smyth for their interest and helpful suggestions during this work.

Palmer Physical Laboratory,
Princeton, New Jersey,
March 24, 1927.

THE NUMBER OF RADIATING ATOMS IN A HYDROGEN DISCHARGE TUBE*

By W. H. Crew and E. O. Hulburt

Abstract

About 90% of the energy radiated from a long hydrogen tube filled with moist hydrogen at a pressure of 0.54 mm of mercury and absorbing 400 watts was found to be carried by the first three lines of the Balmer series. From the measured values of this energy and of the relative intensities of Hα, Hβ and Hγ, the number of quanta of these lines emitted per atom per second was calculated to be 2.84, 0.43 and 0.10, respectively.

A GLASS hydrogen discharge tube may be arranged to emit the Balmer lines of hydrogen in great purity, their total energy being much greater than that of the other spectral radiations, such as the infra-red atomic lines, the spectrum of the molecules and the continuous spectrum. If the entire energy radiated from the tube in all directions is measured, if the number of atoms in the discharge tube is known, and if the relative intensities of each of the Balmer lines is known, the average number of quanta of each Balmer radiation emitted by each atom per second may be calculated. Experiments based on these ideas are described in the following pages. It has been found, for example, that in the case of Hα under, let us say, normal discharge conditions this number is of unit order.

Apparatus. The discharge tube consisted of a straight tube of Pyrex glass 79 cm in length and of internal diameter 9 mm, with long side tubes leading to bulbs containing the electrodes, to a pressure gauge, to the pumps and to the hydrogen. The tube was excited by a 1 KW, 30 KV, 25 cycle transformer, the electrical energy in the tube being taken to be the product of the current and voltage.

Calibration of the thermopile. The radiation from the tube was measured by a thermopile and Paschen galvanometer, the thermopile being diaphragmed so that only about 2mm² were exposed to the radiation. An energy calibration was effected by observing the deflection caused by the radiation from a calibrated ribbon filament tungsten lamp. We are indebted to Dr. H. T. Wensel of the Bureau of Standards, who kindly loaned us the lamp and furnished its calibration, i.e. the temperature-current curve. With the filament at 2560° Kelvin and diaphragmed so that an area 0.12 cm² was exposed, the galvanometer deflection caused by the radiation, emitted normally from the surface, falling on the thermopile a meter away was 66 mm. A calculation of the spectral energy curve of the tungsten, by means of the black body formula and the emissive powers[1,2] of tungsten,

* Published by permission of the Navy Department.

[1] Worthing, Phys. Rev. **10**, 377 (1917).

[2] Weniger and Pfund, Phys. Rev. **14**, 477 (1919).

showed that 65 watts/cm² were emitted normally, and that 99% of this was in the spectral region of transparency of the glass bulb, 0.32 to 3μ. The glass bulb thus caused a loss of 9%, 1% being due to absorption and 8% to reflection. At a meter's distance the flux of energy was

$$0.91\times65\times0.12\times10^{7}\div10^{4}=7.10\times10^{3}\ \text{ergs/cm}^2.$$

This produced a deflection of 66 mm. Therefore 1 mm meant an energy flux of 108 ergs/cm².

Total energy from the hydrogen tube. With moist hydrogen in the tube at a pressure of 0.54 mm of mercury excited with 400 watts (66 milliamperes×7 kilovolts) the Balmer lines were intense, fourteen of them appearing on plates taken in five minutes with the large quartz spectrograph. Other lines and the continuous hydrogen spectrum of course were also on the plates, but with relatively feeble intensity. In addition there are certain infra-red lines from atomic hydrogen of wave-length below 3μ which may come through the glass, i.e. the entire Paschen series and a portion of the Brackett and Pfund series. The entire intensity I_R of these infra-red lines was compared with the intensity I_B of all the Balmer lines by means of a Corning "Heat Transmitting" glass filter. Measurements showed that this filter transmitted 83% of the energy from 1.4 to 2.7μ and was opaque below 0.7μ. With the thermocouple at the side of the tube, the unscreened radiation produced a galvanometer deflection of 86 mm and when screened by the filter a deflection of 3 mm. Therefore

$$I_B/I_R=86\times0.83/3-1=22.8.$$

This number was not very accurate, depending as it did on a 3 mm deflection, but sufficed to show that about 95% of the radiation from the tube was carried by the Balmer lines, the weak molecular lines, the continuous spectrum, etc.

A 43 mm deflection was observed with the thermopile 5 cm away from the side of the tube, (the excitation being always 400 watts and pressure 0.54 mm of mercury), and at other distances up to 15 cm the deflections were proportional inversely to the distance. The total energy E_s ergs/sec radiated from the side of the tube was, therefore,

$$E_s=2\times5\times\pi\times79\times43\times108=1.153\times10^{7}\ \text{ergs/sec.}$$

Radiation from the end of the tube produced a deflection of 122 mm which remained constant when the thermopile was moved from 2 to 5 cm from the end of the tube. The total energy E_e radiated from the two ends of the tube was, then,

$$E_e=2\pi\times0.45^2\times122\times108=0.00168\times10^{7}\ \text{ergs/sec.}$$

The entire energy E radiated from the tube was, neglecting the end effects of E_s,

$$E=E_s+E_e=1.155\times10^{7}\ \text{ergs/sec.}$$

The efficiency of the tube. The total length of the hydrogen tube was 300 cm. When the tube was absorbing 400 watts, a section 79 cm long absorbed 105 watts and radiated 1.155 watts. Therefore the efficiency of the tube as a radiator of Balmer energy was about 0.9%.

Relative energy from the side and end of the tube. The small amount of energy delivered from the ends of the tube compared with that from the side deserves a few remarks. The measurements showed that $E_s/E_e=685$. An exact theoretical derivation of this ratio would be tedious. It is evident, however, that the radiation from elements of the tube remote from the ends does not get out to the ends in full amount mainly because it escapes through the glass walls of the tube when the angle of incidence is not too close to grazing; it also suffers absorption on its way along the tube. For example, only 60% of the energy of rays striking the walls at a grazing angle of 10° is reflected (60% being the average of the reflecting powers 72 and 48%, for the electric vector parallel and normal, respectively, to the surface, as calculated from Fresnel's equations, taking the refractive index of the glass to be 1.5). Therefore after a few reflections practically all the energy of these rays has passed out to the side. It is only when the grazing angle becomes less than 3° that the average reflecting power is above 80% and that the light proceeds along the tube without much loss. For a grazing angle of 3° the calculated ratio E_s/E_e was greater than 400. If the absorption of energy along the tube were taken into account (there are no exact data yet for the absorption) E_e would be decreased and the number 400 increased, and we might expect satisfactory theoretical agreement with the observed number 685. Silvering the external walls of the tube would increase E_e; this effect was demonstrated qualitatively by Merton and Johnson.[3] In the present instance we surrounded the tube throughout its length by mercury, and obtained a galvanometer deflection of 180 with the thermopile at the end of the tube, whereas without the mercury the deflection was 122.

Relative intensities of Hα, Hβ, *and* Hγ. The relative intensities of the first three lines of the Balmer series were obtained by a spectrophotometric comparison with the spectrum of the calibrated tungsten lamp. When the discharge tube was filled with moist hydrogen at a pressure of 0.54 mm of mercury and was absorbing 400 watts, the relative intensities of the Balmer lines in the radiations from the side and the end of the tube were; side, Hα:Hβ:Hγ=1.00:0.207:0.054; end, Hα:Hβ:Hγ=1.00:0.40:0.08. These values and those of other observers show some variance. Although this is perhaps to be ascribed to widely differing experimental conditions, the question of the Balmer intensities can hardly be regarded as a settled one. For example Merton and Nicholson[4] found that in a small capillary tube Hα: Hβ:Hγ as 1.00:0.264:0.183, and Nutting and Tugman[5] 1.00:0.315:0.0055. In the electrodeless discharge in hydrogen Schlesinger[6] observed that Hα:Hγ=1.00:0.06.

The fact that the intensity of Hα compared to the other lines is relatively less from the end of the tube than from the side is of course to be ascribed to absorption in the luminous hydrogen. It would follow that in the radiation from the end of the tube only the layers near the end are effective con-

[3] Merton and Johnson, Phil. Mag. **46**, 448 (1923).
[4] Merton and Nicholson, Phil. Trans. **217** (1917).
[5] Nutting and Tugman, Bull. Bur. Stand. **7**, 49 (1911).
[6] Schlesinger, Zeits. f. Phys. **39**, 215 (1926).

tributors of Hα, whereas for Hβ and Hγ the more remote layers are effective as well. A pretty demonstration of this is obtained by gazing into the tube through a red glass which transmits only Hα; in this case one sees hardly more than 50 cms into the tube. With a blue screen opaque to Hα and transparent to Hβ and Hγ the far end of the tube 80 cms away is quite distinct. The experiment is exactly in the manner of the spectroheliograph for seeing into the sun.

The number of quanta emitted per atom. In accordance with the foregoing measurements 90% of the energy delivered by the tube was carried by the first three Balmer lines, 5% by the infra-red lines, and the remaining 5% by the higher members of the Balmer series, the molecular lines, the continuous spectrum, etc. Then with $H\alpha:H\beta:H\gamma = 1.00:0.207:0.054$, and with $E = 1.155 \times 10^7$, the total energy each second emitted from the tube in the form of Hα comes out to be 8.24×10^6 ergs; this amounts to 2.75×10^{18} quanta of Hα. We have shown in another investigation[7] that the hydrogen under the conditions of the present experiment was almost entirely atomic. Therefore the Hα energy was emitted by 9.65×10^{17} atoms (the pressure in

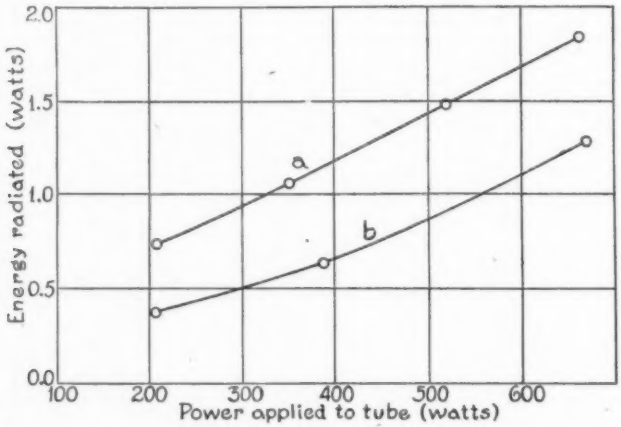


Fig. 1. Total radiation E as a function of the power for constant pressures 0.47 and 0.72 mm of mercury, curves *a* and *b*, respectively.

the discharge tube being 0.54 mm of mercury), and on the average each atom in the tube emitted 2.84 quanta of Hα per second. Similarly, the average numbers of Hβ and Hγ quanta per atom per second were 0.43 and 0.10 respectively.

Pfund[8] has found that the total intensity of the Lyman series from much the same sort of hydrogen discharge as that of the present experiment was 8.8 times that of the Balmer, Paschen and Brackett series all added together. We may then conclude that the order of magnitude of the number of Lyman quanta emitted per atom per second was about 10.

Variation of the radiated energy with the power and pressure in the tube. The manner in which the total energy E varied with the power and pressure

[7] "Pressures in Discharge Tubes," to be published soon.

[8] Pfund, Journ. Optical Soc. Amer. **12**, 467 (1926).

in the tube is shown in the curves of Figs. 1 and 2, the curves *a* and *b*, Fig. 1, which are for constant pressures of 0.47 and 0.72 mm of mercury, respectively, and the curve of Fig. 2 for a constant power of 400 watts. The full line portion of this curve was obtained by pumping the pressure down in steps and observing the galvanometer deflection with the tube lighted at each step. Towards the end of such a procedure at the lower pressures the tube became whitish and no longer glowed with the crimson radiance characteristic of a pure Balmer spectrum. This was due, it was supposed, to the burning off of the water vapor from the walls of the tube, thereby permitting them to catalize the atoms to the molecular state. If the curve was repeated each point being obtained by refilling the tube with fresh moist hydrogen and then

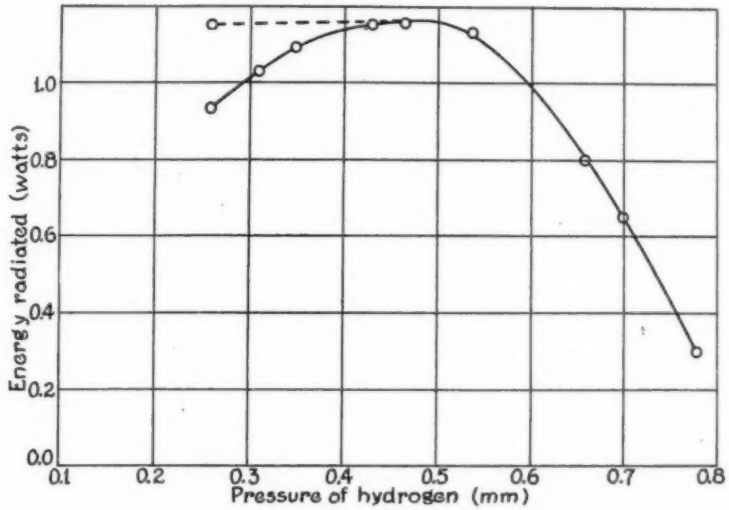


Fig. 2. Total radiation E as a function of the pressure for constant power of 400 watts.

pumping down to the desired pressure, the dotted branch of the curve of Fig. 2 was obtained, the curve for pressures above 0.45 being unchanged. In Fig. 1 for powers above 300 watts the hydrogen was practically all atomic, and the number of quanta emitted per atom was therefore proportional to E. From the highest point of curve *a*, Fig. 1, with 665 watts in the tube, each atom emits 5.2 quanta of Hα per second. If we suppose that the time during which the atom remains in the excited state is 10^{-8} seconds, it is seen that the atoms of hydrogen, even under rather violent discharge conditions, are on the average in an unexcited state a relatively large part of the time.

In conclusion, we may remark that the present method is by no means restricted to the hydrogen lines, although, to be sure, these are comparatively easy to isolate spectroscopically, but is directly applicable to the determination of the number of quanta emitted per atom, or molecule, of any spectral line.

NAVAL RESEARCH LABORATORY,
WASHINGTON, D. C.,
February 17, 1927.

A STUDY OF THE POLARIZATION OF THE LIGHT FROM HYDROGEN CANAL RAYS

By K. L. Hertel

Abstract

Polarization of light from hydrogen canal rays and its rate of decay.—Light from hydrogen canal rays (principally Hβ) was found to be partially polarized, with the electric vector of the stronger component in the direction of motion of the particles. The amount of this polarization varied over a considerable range: the maximum polarization observed was about 10 percent. Measurements of the polarization at different positions along the canal ray bundle show that the polarization dies away more rapidly than does the intensity. Its half-value time is about one-third that for the intensity.

Effect of a transverse electric field on the polarization of light from hydrogen canal rays.—When an electric field at right angles both to the canal ray bundle and to the direction of observation is applied to the canal rays the polarization changes rapidly (in less than 10^{-9} sec.) at the points of entry to and exit from the field. The change is in the same direction at both entry and exit and is such that the component of the electric vector perpendicular to the direction of motion is increased relative to the parallel component. The change increases with the strength of the field up to 300 or 500 volts per cm after which the increase is small. In a weak uniform field (less than 200 volts per cm) the polarization appears to die out at about the same rate as with no field. In stronger uniform fields there is a tendency for the light to become polarized with the stronger component of the electric vector in the direction of motion. There is some evidence of periodicity in the polarization as the particles pass through a uniform field.

WHILE studying the effect of an electric field upon the radiating atom, Stark[1] observed qualitatively that the light from the canal rays of hydrogen was partially polarized. In 1915 Stark and Luneland[2] studied this polarization quantitatively, and found that the light from the moving particles was polarized, while that from the particles at rest was not polarized. They expressed the polarization as the ratio of the component vibrating in the direction of motion to that vibrating at right angles to it, and this ratio varied from 1.20 to 1.35 for the series lines of hydrogen. If these canal rays are allowed to pass through a small hole in the cathode and into a chamber where the pressure is maintained as low as possible, the intensity of the bundle dies out with distance from the hole. This rate of dying out has been studied by Wien[3] and Dempster.[4]

It would be expected from the observations of Stark and Luneland that the light from the bundle entering the high vacuum chamber used by Wien

[1] Stark, Verh. d. D. Phys. Ges. **8**, 104 (1908); J. Stark u. H. Kirschbaum Ann. d. Physik **43**, 1002 (1914).

[2] Stark and Luneland, Ann. d. Physik **46**, 68 (1915).

[3] Wien, ibid. **60**, 597, 1919; ibid., **66**, 230, (1921); ibid., **73**, 483, (1923).

[4] Dempster, Phys. Rev., **15**, 138, (1920); Astro. Jour., **57**, 193, (1923).

and Dempster would be partially polarized. Rupp[5] recently observed qualitatively that this light was partially polarized, showing that the polarization observed by Stark and Luneland persisted. The problem attacked in this series of experiments was a study in more detail of the polarization of the light from this bundle in high vacuum. It is to be noted that in this high vacuum chamber the particles are neutral, excited, moving with a high velocity, and disturbed very little by collisions with other particles. If now, these particles are subjected to an electric field or a magnetic field and an orientation is produced, it might be expected that the polarization would be changed, and since the particles have a high velocity, a "history" of the effect could be obtained by observing the polarization at various points along the path of the particles. The results of the experiments discussed here show that the light from the hydrogen canal rays at low pressure is partially polarized, and that this polarization dies out with distance from the cathode. They show further that polarization effects are produced by electric fields at right angles to the motion of the particles.

Experimental

The method used in producing the hydrogen canal rays in high vacuum was similar to that used by Wien and Dempster. Purified hydrogen was allowed to flow from a reservoir, through a capillary tube and liquid air trap into the discharge tube. Rectified current was sent through the discharge tube to produce the canal rays, which then passed through a small hole (0.48 mm diam.) in the cathode into the observation chamber. Here the bundle was photographed through a calcite crystal and the two images measured on a microphotometer. The gas that passed through the hole with the canal rays was pumped out by a rapidly acting pump, and in this way the pressure was kept low in the observation chamber.

The hydrogen was taken from a commercial steel tank and purified by slowly passing it through activated charcoal immersed in liquid air. The gas was then stored in a reservoir and introduced into the discharge tube as needed. In order to adjust the pressure in the discharge tube, it was necessary to adjust the rate of inflow of the gas. This was accomplished by using a capillary tube 20 cm long, having a bore of 0.5 mm, and inserting in the bore a glass rod slightly tapered and a little smaller than the bore. The glass rod was made by drawing down larger rod until the proper size was obtained. The piece of iron *F*, Fig. 1, was fastened to the large end of the glass rod so that it could be moved by means of a magnet from the outside. By adjusting the glass rod the resistance to the flow of gas could be changed to give any discharge-tube pressure desired. Using a reservoir pressure of 25 cm of mercury, the pressure in the discharge tube was changed from 0.14 mm to 0.07 mm of mercury when the rod was moved 8 cm.

As shown in Fig. 1, the discharge tube *D* was separated from the observation chamber *O* by the cathode (Fig. 2) resting on the ground joint *G*. The discharge tube proper was 55 cm long and 2.3 cm in diameter. Two different

[5] Rupp, Ann. d. Physik **99**, 1 (1925).

observation chambers were used in these experiments. The first was a cylindrical tube of Pyrex glass about 4.4 cm in diameter and the bundle observed through the cylindrical wall of the tube. The second observation chamber (O, Fig. 1) was designed to reduce to a minimum any polarization that might be introduced by the glass wall. It had a large tube extending in the direction of the camera and a good piece of plate glass fastened to the end of it with wax. The calcite crystal C which had been recently polished was properly oriented and cemented to this plate with Canada balsam, thus leaving only one reflecting face to introduce polarization. The lens of the camera was placed near the calcite crystal and the glass plate, so that any polarization introduced by strains in the glass plate would not be localized in the image.

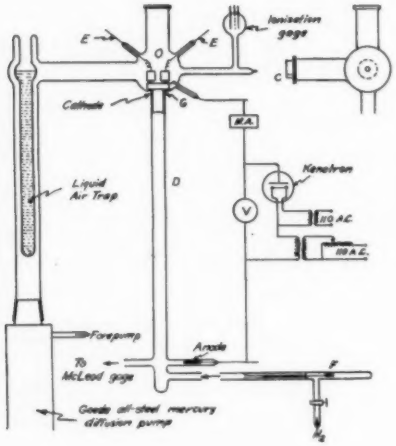


Fig. 1. Diagram of apparatus.

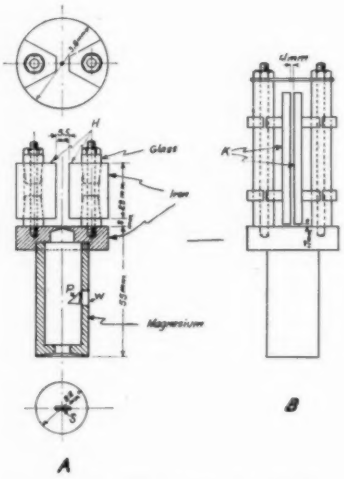


Fig. 2. Diagrams of cathodes.

The pressure in the discharge tube was measured by a MacLeod gage and in the observation chamber it was measured by an ionization gage which had been calibrated with the MacLeod gage. The current for the discharge tube was furnished by an alternating current transformer, rectified with one kenotron, and thus giving only one-half of the cycle. The current was measured by the direct current milli-ammeter M.A. and the voltage across the tube measured by the Braun voltmeter V.

The cathodes used in these experiments are shown in Fig. 2. The lower part, which extended down into the discharge tube, was made of magnesium to eliminate sputtering. P was a totally reflecting prism which reflected the light from the slit S through the opening W into the slit of a spectroscope for observing the Doppler effect. This magnesium cup was fastened to the cathode proper which in turn rested on the ground joint. In the center of the cathode was a hole 0.48 mm in diameter which allowed the canal rays to pass into the observation chamber. Cathode "A" was used to apply either a magnetic or an electric field to the bundle, the poles H acting either

as magnetic poles or as condenser plates. When a magnetic field was used the magnet was placed just outside the walls of the tube. On cathode "*B*" the condenser plates were made adjustable and set close together and near the cathode as shown in Fig. 2. The condenser plates were joined to the leads *E* (Fig. 1) which were in turn connected to a potentiometer for applying the field. Care was always taken to adjust the potential so that the potential of the cathode (which was grounded) was midway between that of the two plates *K*.

It was necessary in these experiments to keep the pressure in the observation chamber as low as possible in order that the number of collisions of the moving particles with the "rest" gas be reduced to a minimum. This was accomplished by connecting a Gaede all-steel mercury diffusion pump to the observation chamber with large tubing and using the special liquid air trap shown in Fig. 1. The total distance from the cathode to the mouth of the pump was about one meter. In this way the ratio of the pressures on the two sides of the cathode could be maintained up to 330 to 1. With wax joints in the system, this ratio was reduced a little.

Method of Photometry

The luminous bundle was studied by photographing it at right angles both to the direction of motion of the particles, and to the direction of the field. The photographs were taken with an ordinary camera through a calcite crystal 1 cm thick. The crystal was oriented so that one image was produced by the light vibrating in the direction of motion of the particles, while the other was produced by the light vibrating at right angles to it. A 0.7 mm slit made of bakelite was placed 8 mm in front of the bundle and parallel to it, to prevent the two images from overlapping as the bundle became diffuse. The images were about 0.5 mm apart on the photographic plate, and the blackening could be easily measured with a microphotometer. Beyond the bundle another piece of roughened bakelite was placed so that no light could be reflected through the slit into the camera. Cramer Hi Speed plates were used and developed with Cramer Contrast Developer. Exposure times of 10 to 20 minutes were found to give the right density to be used on the microphotometer. The microphotometer was of the thermopile type, having a Coblentz thermopile and a Leeds and Northrup high sensitivity galvanometer.

In order to convert the microphotometer readings into relative intensities a series of intensity spots were placed on every photographic plate and a calibration curve made for each plate. The intensity spots were formed on the plate by allowing light from a uniformly illuminated screen to pass through holes of various sizes and to fall on the plate 7 cm away. There was a velvet lined tube leading from each hole to the plate so that the light falling upon any one part of the plate came through only one hole. The relative intensity with which the plate was illuminated at any one point was directly proportional to the area of the hole through which the light passed, and from the relative areas of the holes the corresponding relative intensities were

determined. A gas-filled tungsten light was used to illuminate the screen after it was found by test to give the same density curve as the light from the region just in front of the cathode. In the microphotometer the slit of the instrument was vertical and was adjusted to less than half the width of the image of the bundle which was also placed vertical. The plate was placed on a horizontal slit 0.6 mm wide, so that only 0.6 mm of the image was measured at a time. This represented from 0.9 to 1.1 mm of the bundle since the reduction of the camera was 1.5 to 1.85 times. In measuring a plate, the intensity spots were first placed over the horizontal slit and moved horizontally past the instrument; in this way the average deflection for each intensity spot was obtained. The two images of the bundle to be measured were then placed across the slit and the deflection for the maximum density of each image was observed. These data were taken at 1 mm intervals along the length of the image. The deflections for the intensities giving the calibration curve for the plate, and from this calibration curve the deflections for the image were changed into relative intensities. Using this method of photometry, the images and comparison are placed on the same plate, exposed for the same length of time to the same quality of light, and developed in the same developer at the same time. Also the microphotometer readings of the two images were taken as near the same time as practical. In this way the photographic plate with the microphotometer acted as a medium for comparing intensities, and consequently the accuracy depended primarily upon the uniformity of both the photographic plate and the microphotometer measurements.

Data and Results

The data in Figs. 3 and 4 were taken with the cylindrical observation chamber and the cathode "*A*" (Fig. 2), and for the data in Figs. 5, 6 and 7 the observation chamber shown in Fig 1 with cathode "*B*" were used. The set of curves shown in each figure was made from the data taken from one photographic plate. I_p was the intensity of the light whose electric vector was vibrating parallel to the direction of motion of the particles, and I_n the intensity of light whose electric vector was vibrating at right angles to this. The ratio I_p/I_n was plotted against the distance along the bundle. Several plates were discarded because of their non-uniformity.

In Fig. 3 *A*, the solid line shows the dying out of the partial polarization with distance from the opening in the cathode, and the broken line shows the dying out of the total intensity. It is seen that the partial polarization decreases at a faster rate than the intensity itself and becomes practically zero by the time the total intensity has reached half value. The remaining curves of Fig. 3 show the effects of various electric fields upon the polarization. The notation "field applied" show the distance over which the field was applied and is the 23 mm distance of cathode "*A*" Fig. 2. The polarization of the light as the particles are entering the observation chamber is approximately the same as with no field, but this changes quite rapidly as the particles enter the field, the light becoming polarized in

the opposite direction by the time the particles are in the uniform field. In this uniform field the polarization dies out at about the same rate as

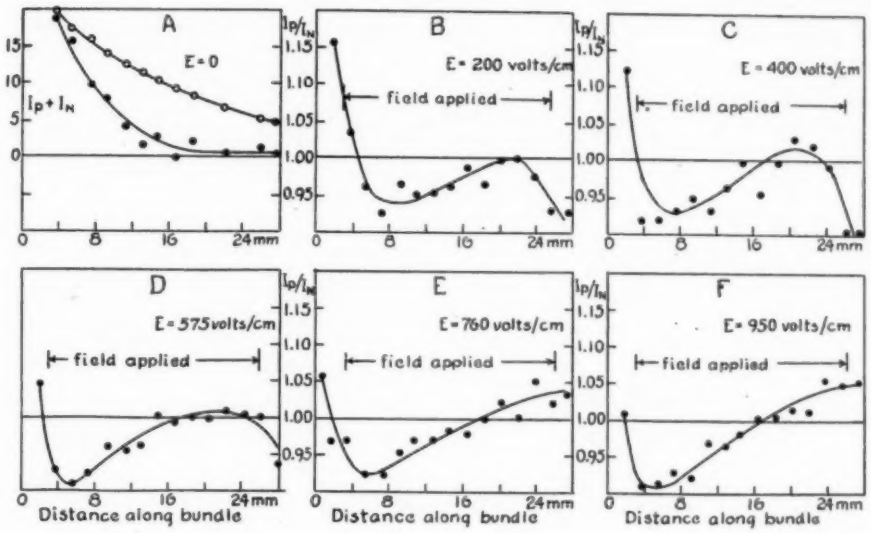


Fig. 3. Showing the variation of intensity and state of polarization of the light along the canal ray bundle. $P = 0.097$ mm, $p = 0.00029$ mm, $V = 5000$ volts, $I = 9.0$ m.a., $S = 5.4$ 10^7 cm/sec.

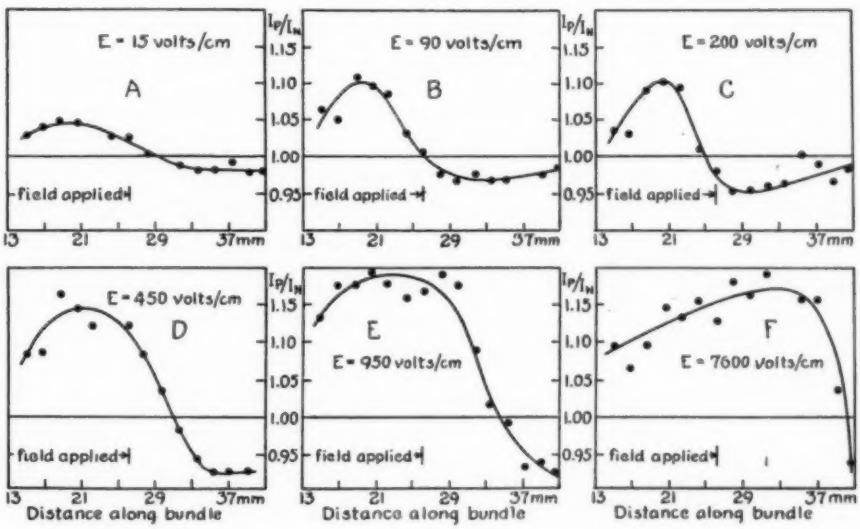


Fig. 4. Showing the variation of the state of polarization of the light along the canal ray bundle. $P = 0.100$ mm, $p = 0.00030$ mm, $V = 4200$ volts, $I = 9.5$ m.a.

with no field at all, and in the stronger fields I_p again becomes greater than I_n. When the particles pass out of this uniform field another change in the

polarization takes place. This change is similar to the change that occurred as the particles entered the field, and I_n again becomes the stronger. It is

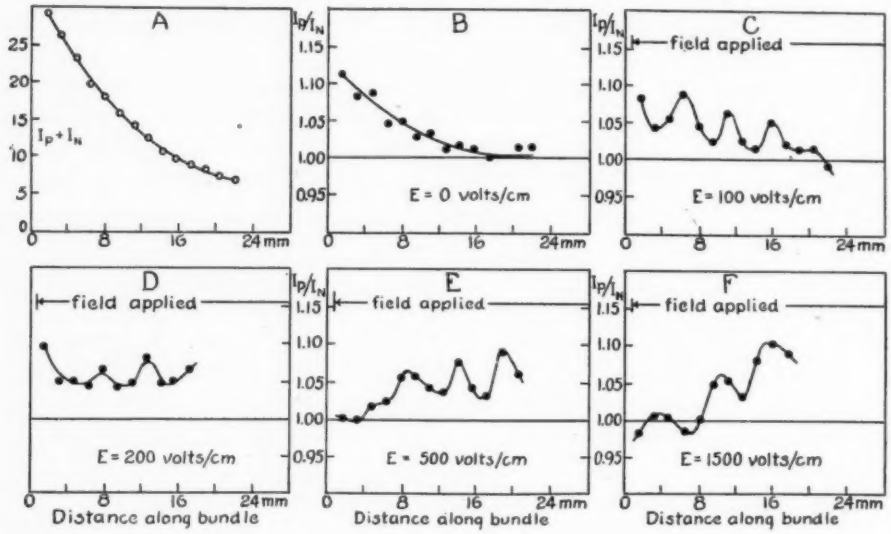


Fig. 5. Showing the variation of intensity and state of polarization of the light along the canal ray bundle. $P=0.080$ mm, $p=0.00034$ mm, $V=6300$ volts, $I=8.0$ m.a., $S=4.1$ 10^7 cm/sec.

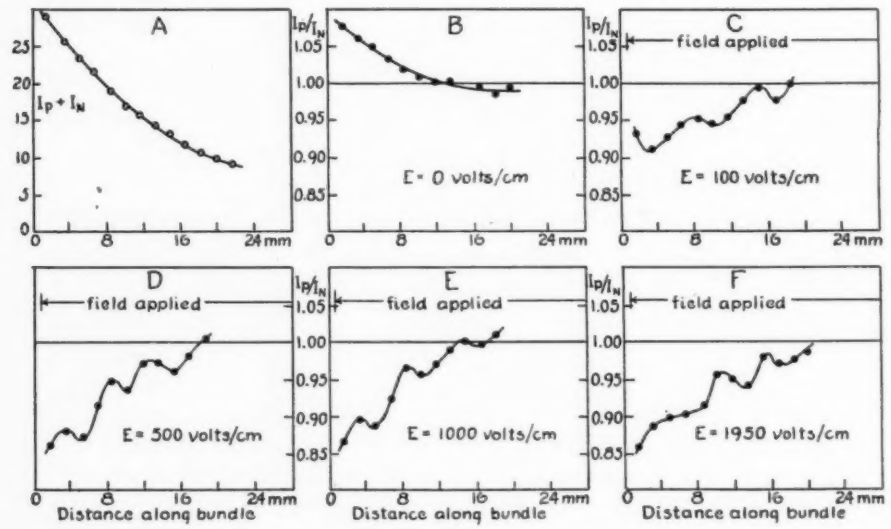


Fig. 6. Showing the variation of intensity and state of polarization of the light along the canal ray bundle. $P=0.0925$ mm, $p=0.00034$ mm, $V=6000$ volts, $I=9.5$ m.a., $S=5.2$ 10^7 cm/sec.

seen that as the field was increased this last change took place later and later, and in the last two curves (E and F) it did not occur at all. In a similar

way the change that took place as the particles entered the field seemed to occur a little earlier with the stronger fields.

In order to confirm the conclusion that a sudden change in the polarization occurred as the particles passed out of the field, a series of photographs were taken of this region of the bundle. The results obtained are shown in Fig. 4 with the field varied from 15 to 7,600 volts per cm. In every case a change occurred, and in general the change occurred later for stronger fields. For the field of 7,600 volts per cm the change took place about 1 cm beyond the end of the condenser plates. In the two curves *B* and *C* of Fig. 4 there is evidence that after this sudden change took place in the polarization, the polarization once more decreased.

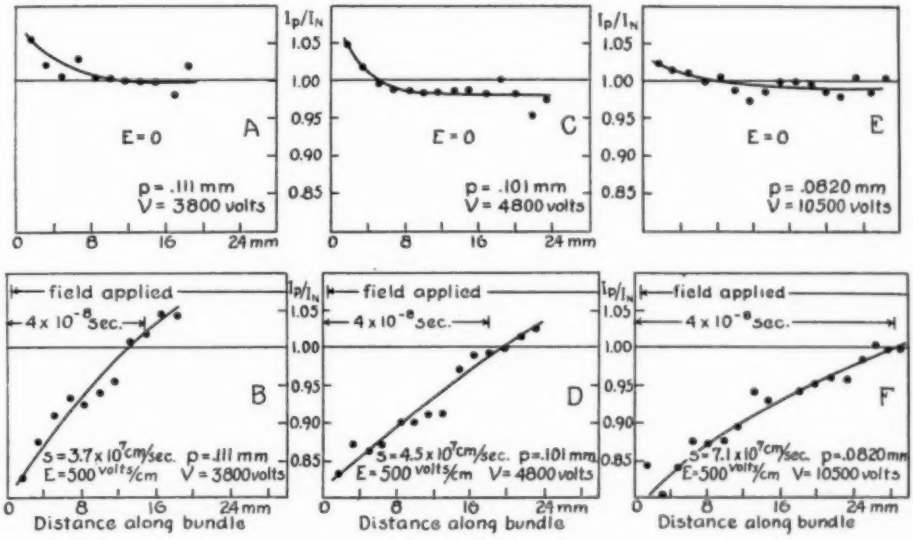


Fig. 7. Showing the variation of the state of polarization of the light along the canal ray bundle for various pressures and potentials in the main discharge tube. $p = 0.00035$ mm, $I = 8.5$ m.a.

The data shown in Figs. 5, 6 and 7 were taken with cathode "*B*" and the observation chamber shown in Fig. 1. The dying out of the polarization is shown in curve *B* of Fig. 5 with no field applied, and *A* is the total intensity curve of the data from *B*. The total intensity was taken as the sum $I_p + I_n$. A smooth curve through the points in *B* gives some idea of the accuracy of the data. If a smooth curve had been drawn through the points in *C* it is plainly seen that the points would be much farther from the curve than in *B*. It is for this reason that a curve was drawn directly through the observed points. When this was done the curve took on the appearance of a "wave" with a certain regularity. In the same way the rest of the curves were drawn directly through the observed points. In the case of *F* another "wave" appears but with a longer wave-length than *C*, and starting in the opposite phase. The curve *E* suggests a combination of two waves, and

when C and F are combined, with the phase in both of them reversed, a curve almost identical with that of E results. The curves in Fig. 6 are drawn just as those in Fig. 5, A being the total intensity curve of B, and B being the polarization curve with no field. Similarly the rest of the curves represent the polarization with various electric fields. If the wave-lengths of C in Figs. 5 and 6 are converted into periods of time, 5 C gives a period of 1.2×10^{-8} seconds, and Fig. 6 C gives 1.3×10^{-8} seconds, the field being 100 volts per cm in both cases. From these data there seems to be some evidence for a periodicity in the polarization in a uniform field, yet the effect is too near the limit of accuracy of the experiment to make the evidence conclusive.

In Fig. 7 the electric field was kept at 500 volts per cm and the pressure in the discharge tube varied to give particles of different velocities. It was found that in the case of the slow moving particles the polarization decreased to zero in a shorter distance than for the faster particles. Since the velocity of the particles was known in each case, the time required for the polarization to reach zero could be calculated. It was found to be about 4×10^{-8} seconds in each case. In these curves the change of polarization produced as the particles entered the field had evidently all taken place before the curves started. This means that the change took place in less than 2×10^{-9} seconds.

When the various photographic plates were compared it was found that the initial polarization appearing in the bundle was not the same for the various plates. No definite reason can be given for this, but it may be due to the presence of small amounts of some impurity like mercury, for it is known that the presence of mercury changes the character of the hydrogen canal rays. The amount of polarization produced as the particles entered an electric field depended upon the strength of the field, increasing rather rapidly with the field until 300 to 500 volts per cm was reached, but after this the increase was small. The amount of polarization introduced also seemed to be independent of the velocity of the particle or the amount of initial polarization.

The bundle was also subjected to a small magnetic field but there was no effect that could be detected.

In conclusion the writer wishes to thank Dr. A. J. Dempster, who suggested the problem, for his interest and helpful suggestions during the investigations.

RYERSON PHYSICAL LABORATORY,
UNIVERSITY OF CHICAGO,
March 3, 1927.

ELECTRON EMISSION FROM THORIATED TUNGSTEN

By S. Dushman and Jessie W. Ewald

Abstract

Constants of the electron emission from a monatomic layer of thorium on tungsten at temperatures from 1000° to 2000°K.—The electron emission for a monatomic layer of thorium on tungsten is best represented for zero field strength by the relation $I=3T^2\epsilon^{-30,500/T}$, where I is expressed in amps/cm². The emission was measured for different states of activation of the filament. If we let θ be the fraction of surface covered with thorium, then for $\theta<0.95$ (approximately) log A_θ varies linearly with b_θ where the emission for the given surface is represented by $I=A_\theta T^2 \epsilon^{-b_\theta/T}$. It is also pointed out that the emission for a monatomic film of thorium on tungsten is greater than that observed for metallic thorium.

Introductory Remarks

As shown in a previous paper[1] the emission data for tungsten and tantalum are in satisfactory agreement with the equation

$$I=AT^2\epsilon^{-b_0/T} \tag{1}$$

where A has the value 60.2 amp./cm² degree². The emission data for molybdenum were not in as good agreement, owing largely to the use of a temperature scale which more recent work has shown to be in error.[2]

Some observations by K. H. Kingdon[3] and further experiments by the writers led to the conclusion that in the case of the emission from monatomic layers, Eq. (1) no longer holds true, at least the constant A has a value different from 60.2. It therefore seemed important to obtain data as accurate as possible on the emission for one such case—that of thoriated tungsten.

As shown by I. Langmuir,[4] the emission from tungsten containing thoria is due to a monatomic layer of thorium on the surface, the thorium atoms being obtained by reduction at high temperatures of some of the thoria throughout the metal and the subsequent diffusion of the thorium atoms to the surface.

Experimental Method

In general, most of the emission data obtained by the writers and their associates have been secured with tubes similar to that described in the paper on the emission from tungsten, molybdenum and tantalum, that is the cathode was in the form of a V-shaped filament (total length 10 to 15 cm) and the anode consisted of a calcium deposit on the walls of the tube, as

[1] S. Dushman, H. N. Rowe, Jessie Ewald and C. A. Kidner, Phys. Rev. **25**, 338 (1925).

[2] A recalculation of the electron emission data for this metal on the basis of Worthing's published data for the radiant emissivity (Phys. Rev. **28**, 190, 1926) leads to the values $A=60.2$, $b_0=51{,}300$, which are also in agreement with results obtained by C. Zwikker.

[3] K. H. Kingdon, Phys. Rev. **24**, 510 (1924).

[4] I. Langmuir, Phys. Rev. **22**, 357 (1923).

shown in Fig. 1 of the above mentioned paper.[1] Some of the data mentioned in the latter part of this paper were taken with such tubes. For the purpose of reference, we will designate such tubes as type A.

However, the most accurate data were obtained on tubes (Type B) in which, instead of a V-shaped filament, a straight filament was used along the axis of the tube, with a molybdenum spring at one end to prevent bowing. Fine tungsten wires were welded onto the leads at each end of the filament and these were used to measure the voltage drop along the filament. The calcium deposit on the wall was obtained from two tungsten spirals (one at each end of the tube) containing calcium wire. A charcoal tube, which was immersed in liquid air during the measurements, was also sealed onto one end of the tube. Whether this extra precaution was really necessary is questionable, as more recent work, carried out since the observations recorded here were made, has shown that the residual oxygen pressure obtained with calcium or magnesium deposited on glass is *much lower* than that obtainable with charcoal in liquid air. However, it is certain that by adopting both these methods of cleaning up residual gases the vacuum attained was so good that the emission from an activated filament remained constant over a long period, and there was no difficulty in obtaining reproducible results.

Temperature Scale

The temperature scale for tungsten used is that worked out by Dr. H. A Jones of this laboratory.[5]

The potential-difference (V) along the filament and the current (A) were measured on precision instruments. A first approximation to the correct temperature was obtained by calculating the value of the function A' ($=A/d^{3/2}$, where d is the diameter). The value of V was then corrected for end-loss effect in the manner indicated in a subsequent section and the corrected value of W' ($=W/ld$ where W is the corrected value of the power input and l is the length) calculated. The corresponding value of T was then obtained from a large scale plot of W' versus T.

Occasional checks on the temperatures calculated in this manner were obtained by direct pyrometry of vacuum lamps made up with the same wire as the filaments in the tubes used for electron emission measurements and aged in the same manner.

The diameter of the wire used was, of course, determined by weighing a long length of it and assuming the density to be 19.35.

Lead-Loss Correction

As the filament is cooled near the leads, it is obvious that the potential difference along the filament, watts radiated, or electrons emitted, are less for a given current than they would be if the whole length of filament between leads were at the same temperature. The ratio between the value of the emission (or watts radiated, etc.) calculated for the latter case and that

[5] H. A. Jones, Phys. Rev. **28**, 202 (1926). See also Forsythe and Worthing, Astrophys. J. **61**, 126 (1925).

actually observed is designated as the correction factor, f. It is evident that for a given length of filament, the lower the temperature, the greater the value of f; also that f must increase as the length of filament is decreased. In the case of emission data from thoriated tungsten, the range of temperatures used is much lower (1000–1600°K) than that for tungsten (1500–2300°K). Hence lead-loss corrections are much more important in this work than in the case of the other metals previously investigated.

The values of f were calculated by means of the relations derived by I. Langmuir.[6] Let H denote any function of the temperature, such as power radiated, luminosity, or electron emission, and let L denote *half the length* of filament between two leads. Also let ΔL_H denote the effective shortening due to cooling *at one lead*. Then:

$$f=\frac{L}{L-\Delta L_H}=\frac{LdV/dL}{(L-\Delta L_H)dV/dL}=\frac{V+dV}{V+\Delta V-\Delta V_H} \tag{2}$$

where V is *one half* the total potential difference along the filament, ΔV is the correction for voltage drop (due to one lead), ΔV_H is the correction (in volts) for loss in value of H (due to one lead).

For lead-loss correction of potential drop in volts, the relation used was

$$\Delta V=.00013(T-400) \tag{3}$$

The value of ΔV_H is a complicated function of b_0 and the temperature. In the following table are given the values of ΔV_H used for the case of a surface completely covered with thorium.

T:	1000	1200	1400	1600
ΔV_H:	0.415	0.49	0.56	0.625

A method which suggested itself for eliminating the uncertainty in the value of the lead-loss correction consisted in *comparing measurements* on two different lengths of the same wire. This method was also used and the results obtained, as shown in a subsequent section, are in agreement with those obtained on the individual filaments after correcting for the effect of leads.

In the case of partly activated surfaces, b_0 is greater than for the fully activated condition and the value of ΔV_H is also different. In the present paper the values of this correction were obtained from the curves shown in Fig. 11 in the General Electric Review paper by the writers.[7]

Correction for Anode Voltage

As pointed out in a previous paper by the writers,[1] the observed emission has to be corrected not only for cooling effect of leads, but also for the effect of anode voltage. Schottky has derived the following relation for calculating

[6] I. Langmuir, Trans. Far. Soc. **17**, Part 3 (1921). See also S. Dushman and Jessie Ewald, Gen. Elec. Rev. **26**, 154 (1923). A more complete discussion of the method of deriving these formulas will appear in the near future in a paper by I. Langmuir and S. Dushman.

[7] It is to be noted that in this paper the values of ΔV_H are wrongly given as for *two* leads; whereas they should apply to only *one* lead.

the emission at zero field strength (i_0) in terms of the emission, i_V, at field strength dV/dx

$$\log_{10} i_V = \log_{10} i_0 + 4.39(dV/dx)^{1/2}/2.30T \qquad (4)$$

(It is assumed that the space currents are much below those corresponding to space charge,—a condition which was fulfilled in all cases.)

Schottky actually showed the validity of this relation for anode voltages up to 5000 for conditions in which the maximum value of dV/dx was considerably greater than those existing in the tubes used in the present investigations. More recent work by Mr. N. B. Reynolds in this laboratory has shown that Eq. (4) is also applicable to thoriated tungsten filaments for field strengths which are many times greater than those worked with in the present investigation.

According to this equation the values of i_0 for a given tube are obtained by plotting log i_V against $V^{1/2}$ at constant temperature. From the values of $\Delta \log i/\Delta V^{1/2}$ obtained for different temperatures an average value of $T\Delta \log i/\Delta V^{1/2}$ was derived and this was then used to calculate the value of i_0 at each temperature.

Emission Data For Fully Activated Surfaces

The most accurate data were obtained from measurements with two tubes, K-363 and K-364, which were made up with axially located filaments and special voltage leads, as described in a previous section. The tungsten wire used contained approximately 1.8 percent ThO_2, and had a diameter of 0.00876 cm.

Tube	Filament Length	Area
364	15.94 cm	0.438 cm²
363	8.05	0.221
	$L_1 - L_2 = 7.89$	$S_1 - S_2 = 0.217$

While exhausting the tubes on the condensation pump, they were baked out for 2 hours at slightly above 360°C, in order to remove all gases from the

Table I

Data for determination of temperature scale.

Filament current (amp.)	P. D. along filament (volts) K363	K364	$\frac{V_1 - V_2}{7.89}$	Corrected P. D. along filament (volts) K363	K364	W'	T
0.25	0.792	1.73	0.119	0.96	1.90	3.40	1109
.30	1.085	2.34	.160	1.285	2.55	5.47	1209
.35	1.421	3.025	.203	1.635	3.24	8.10	1300
.40	1.796	3.769	.250	2.01	3.99	11.40	1385
.45	2.203	4.587	.302	2.43	4.82	15.50	1469
.50	2.642	5.454	.356	2.87	5.68	20.30	1545
.55	3.105	6.387	.416	3.35	6.63	26.10	1621
.60	3.610	7.372	.476	3.83	7.60	32.62	1695
.80	5.886	11.854	.757	6.10	12.09	69.20	1942
1.00	8.637	17.250	1.091	8.79	17.42	125.0	2220

TABLE II

Emission data for calculating the thermionic constants of thoriated tungsten filaments.

Emission data K-364					K-363	Difference in emission		
T	i_0	f	$\log_{10}I+6$	f(obs)	i_0	Δi_0	$\log_{10}I+6$	$\log_{10}(I/T^2)+12$
1109	1.17×10^{-6}	1.93	0.713	1.80	1.31×10^{-7}	1.04×10^{-6}	0.679	0.589
1151	3.18	1.77	1.109	1.63	6.24	2.56	1.072	.950
1209	1.40×10^{-5}	1.63	1.717	1.55	3.29×10^{-6}	1.07×10^{-5}	1.692	1.527
1244	3.17	1.56	2.052	1.50	8.34	2.34	2.033	1.843
1300	1.09×10^{-4}	1.48	2.565	1.52	2.67×10^{-5}	8.23	2.579	2.351
1336	1.94	1.44	2.805	1.36	6.27	1.31×10^{-4}	2.780	2.528
1385	5.38	1.39	3.232	1.42	1.59×10^{-4}	3.79	3.240	2.957
1421	9.46	1.36	3.467	1.36	3.08	6.38	3.468	3.163
1469	2.09×10^{-3}	1.32	3.800	1.32	7.23	1.37×10^{-3}	3.800	3.466
1500	3.32	1.30	3.993	1.24	1.29×10^{-3}	2.03	3.971	3.619
1545	7.14	1.28	4.319	1.29	2.54	4.60	4.326	3.948

glass walls and from the charcoal; the filaments were then flashed at about 2400°K for a couple of minutes and the calcium evaporated onto the walls. The exhaust was continued for a few minutes and the tubes sealed off.

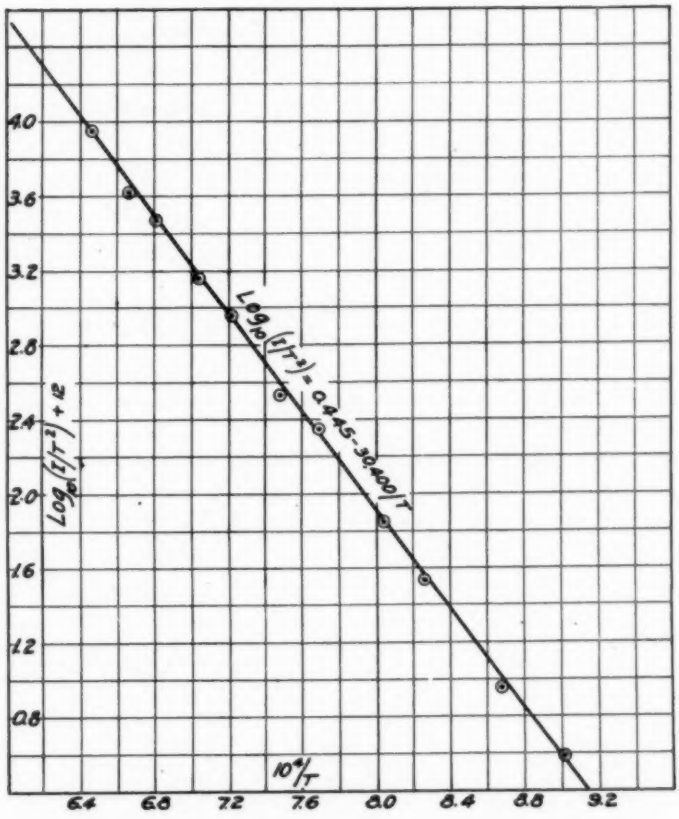


Fig. 1. Values of log (I/T^2) plotted against $10^4/T$. Tube K363.

Before taking data, the filaments were aged for 3 hours at 2400°K and then flashed for 1.5 minutes at 2900°K to reduce thoria. They were then activated at 2100°K or lower to a maximum emission, using 1500°K as testing temperature.

The data for the determination of temperature scale are given in Table I, while Table II gives the emission data used for calculating the thermionic constants. Under i_0 are given the emission data (after correcting for anode voltage), and in the case of K-364 there are also given the values of f used in calculating log I for each value of T. The differences between the values of i_0 at constant T for the two filaments are tabulated under Δi_0 and the last two columns give the corresponding values of log I and log (I/T^2).

From these values of log I and the values of i_0 observed for K-364 values of the correction factor for the latter filament were calculated. These are given under f (obs.).

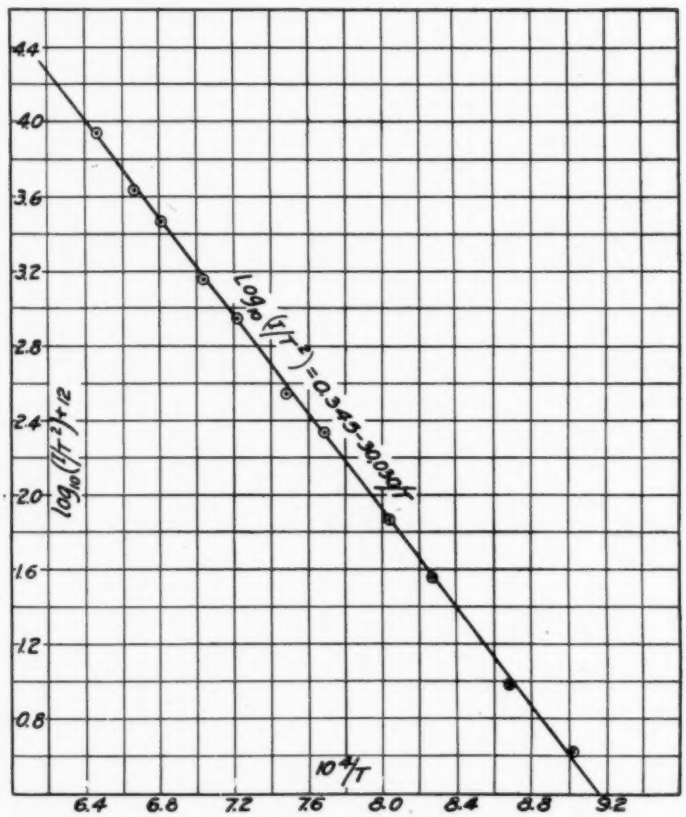


Fig. 2. Values of log (I/T^2) plotted against $10^4/T$. Tube K364.

Fig. 1 shows a plot of the values of log (I/T^2) given in the last column of Table II. Using the method of least squares these data give the values

$$A = 2.85 \text{ amps/(cm}^2\text{deg.}^2\text{)}; \; b_0 = 30{,}400 \text{ (deg. K)}.$$

Fig. 2 shows a similar plot of the data obtained for K-364. The resulting values are:

$$A=2.21, \quad b_0=30,030.$$

While the values of A and b_0 calculated for each set of data are slightly different, it is evident from the data given in Table II as well as the plots in the two figures, that the emission data are practically identical.

Sources of Error

The possible sources of error involved in an accurate determination of the thermionic constants for an electron emitter such as a monatomic film of thorium on tungsten are even more numerous than those involved in measurements with pure metals. In the following section these are discussed briefly.

Incomplete activation. In order to obtain a completely covered film, special care must be taken to activate the filament for a long period at as low a temperature as possible. The exact procedure differs not only with the diameter of the filament, but also with the content of thoria and other factors which depend upon the previous metallurgical history of the wire. As will be shown in a subsequent section, a surface which is only 99 percent covered gives an emission which is approximately 90 percent of that of a fully covered film.

Positive ion bombardment. Even an extremely low pressure of residual gas (10^{-6} mm of Hg or less) will cause a considerable decrease in emission owing to bombardment by positive ions, and as shown by Kingdon, this effect increases rapidly with anode voltage. This was avoided in the present investigation by using calcium volatilized on the glass.

Temperature scale. This is undoubtedly the greatest source of error in all emission measurements. As it was impracticable to pyrometer the filaments *in situ*, the temperatures were calculated from the corrected power input or from the values of $V'A'^{1/3}$. However, for the same radiation intensity, different filaments may vary in temperature by as much as one percent from the average values given in the tables of characteristics, depending not only on the aging schedule, but also on the nature of the wire.

Now since

$$dI/I=(2+b_0/T)dT/T$$

it is evident that a one percent change in temperature at $T=1000$ causes a 30 percent change (approximately) in emission. Thus it is quite possible, especially at lower temperatures, to obtain a variation in emission at apparently the same temperature of as much as 30 percent.

End loss correction. The data for K-363 illustrate well the cooling effect of leads on short filaments. The values of f calculated for this case ranged from 1.75 at $T=1545$ to 2.12 at 1421 and to much greater values at lower temperatures. Consequently no accurate calculations could be made on the basis of the data for this tube alone. However, an inspection of Table II

shows that when the data for K-364 and K-363 were combined, values of log I were obtained which were in good agreement with those obtained with K-364 alone, after introducing a correction for end loss. The agreement between values of f (obs), calculated in the manner discussed in a previous section, and values of f as actually used, is satisfactory, as it is within the limits of error of temperature determination.

Obviously the correction for end losses could be avoided by a construction of tube involving the guard ring principle. Data obtained on such a tube (No. 204) are given in Table III. The filament used had a diameter of 0.0103 cm and a total length of 19.65 cm. The length of the central portion on which emission data were taken was 10.3 cm. The anode consisted of three separated magnesium deposits on the glass wall.

TABLE III

Data obtained with tube in which end corrections were made unnecessary by the use of guard rings.

T	log $(I/T^2)+12$	$10^3/T$	I	T (calc)
1155	.9368	0.8658	1.15×10^{-5}	1148
1216	1.4998	.8224	4.67	1208
1276	2.0150	.7836	1.69×10^{-4}	1266
1335	2.4579	.7491	5.12	1323
1385	2.8600	.7219	1.39×10^{-3}	1378
1453	3.3077	.6882	4.29	1447
1515	3.7100	.6601	1.18×10^{-2}	1511
1612	4.2738	.6204	4.88	1615

The fourth column gives the values of I (after correcting for Schottky effect) as calculated from the emission measurements on the central portion of the filament, while the second column gives corresponding values of log (I/T^2). The values of the thermionic constants obtained from the plot were $A=6.2$; $b_0=31{,}600$.

Comparing emission data as observed at corresponding temperatures, on this tube and on K-363, it is found that the latter are slightly higher. The last column of Table III gives values of T which would correspond to the observed values of I if we assume the thermionic constants $A=3$, $b_0=30{,}500$, which, as will be pointed out below, we believe to correspond to maximum emission data.

The difference between the values of T (calc) and values given in the first column is within the limits of experimental error, especially at the lower temperatures.

THERMIONIC CONSTANTS FOR FULLY ACTIVATED SURFACE

While observations have been made on a number of other tubes, the writers believe that the data obtained on K-364 and K-363 are the most accurate, since they correspond to maximum emission observed at any temperature. Taking into consideration the different possible sources of error, these results are best represented by the thermionic constants

$$A=3.0;\ b_0=30{,}500.$$

Table IV gives emission data calculated for the range $T=1000$ to $T=2000$°K. It is necessary to observe in this connection that owing to evapora-

tion of thorium, the actually observed emission tends to be less than that given in the table at temperatures above 1800°K approximately. The third column in this table gives the efficiency of emission in amperes per watt—a property which is of extreme importance in the practical utilization of such

TABLE IV

Emission data for a thoriated tungsten filament calculated for the range 1000° to 2000°K.

T (°K)	I (amp/cm²)	I/W (amp/watt)	n $d\ln I/d\ln T$
1000	1.73×10^{-7}	2.86×10^{-7}	32.5
1100	3.31×10^{-6}	3.21×10^{-6}	29.7
1200	3.95×10^{-5}	2.37×10^{-5}	27.4
1300	3.27×10^{-4}	1.27×10^{-4}	25.5
1400	2.03×10^{-3}	5.28×10^{-4}	23.8
1500	1.00×10^{-2}	1.811×10^{-3}	22.3
1600	4.06×10^{-2}	5.22×10^{-3}	21.1
1700	1.40×10^{-1}	1.29×10^{-2}	20.0
1800	0.428	3.03×10^{-2}	19.0
1900	1.164	6.28×10^{-2}	18.
2000	2.864	1.20×10^{-1}	17.3

filaments. The last column gives the value of the exponent n in the approximate equation

$$I = AT^n, \text{ where obviously } n = 2 + b_0/T.$$

The emission data actually obtained with different sizes of wire and in various types of tubes may vary from the values given in Table XI by as much as 25 percent, owing to experimental errors, such as those mentioned in previous paragraphs.

The following table (V) gives a comparison between emission data as observed on various tubes and values calculated from the observed power input in accordance with data given in Table IV. In all cases, corrections were made for lead losses and Schottky effect.

TABLE V

Comparison of emission data observed with values calculated from data of Table IV.

Tube No.	T	I (obs.)	I (calc.)
202	1450	3.2×10^{-3}	4.3×10^{-3}
	1650	5.25×10^{-2}	7.2×10^{-2}
161	1212	4.8×10^{-5}	5.0×10^{-5}
	1352	7.7×10^{-4}	8.5×10^{-4}
	1473	7.6×10^{-3}	6.5×10^{-3}
92B	1030	3.3×10^{-7}	4.5×10^{-7}
	1100	2.6×10^{-6}	3.3×10^{-6}
	1190	2.7×10^{-5}	3.0×10^{-5}
	1290	2.3×10^{-4}	2.6×10^{-4}
	1403	1.9×10^{-3}	2.0×10^{-3}
	1528	1.9×10^{-2}	1.6×10^{-2}

In each of these tubes the wire used was approximately 0.010 cm in diameter, but differed in thoria content and also in regard to other manufacturing details. The agreement between I (obs.) and I (calc.) is within the limits of experimental error in practically all the cases.

The following data (Table VI) were obtained with a thoriated wire 0.00403 cm diam. (1.59 mil) such as used in construction of commercial UX-201A tubes. The tubes used for this experiment were exhausted in the same manner as commercial 201A tubes. The filaments ($l=4.45$ cm) were mounted in the axis of a 0.5 inch diameter cylinder (about 1.5 inches long). The temperature was calculated from the observed power input (after correcting for lead-loss). The table gives the potential drop along the filament and the filament current, as well as the observed emission, while the last column gives the value of I (calc.) as taken from a curve plotted from the data in Table IV.

TABLE VI

Observed and calculated thermionic emission in a tube whose thoriated filament and manner of exhaustion were similar to those of the commercial 201A tubes.

Filament current (amp)	P. D. along filament (volts)	T	Emission at 100 volts (milliamp)		I (obs)	I (calc)
0.22	4.00	1825	24.0	1.40	0.595	0.550
.20	3.36	1740	9.7	1.47	.253	.220
.18	2.88	1650	3.05	1.54	.084	.076
.16	2.32	1550	0.82	1.69	.025	.021

The difference between I (obs.) and I (calc.) is easily accounted for by the effect of anode voltage. Recalculated for zero field strength the values of I (obs.) would have to be decreased about 10 to 15 percent.

As a matter of fact, numerous series of observations on commercial radiotrons containing thoriated filaments show uniformly good agreement with the values given in Table IV, after allowances are made for lead losses and probable error in temperature determination, provided, of course, that care has been taken to activate the filament completely.

VARIATION IN EMISSION WITH DEGREE OF ACTIVATION

Langmuir has defined θ, the fraction of the surface covered with thorium atoms, thus:

$$\theta_{\mathrm{I}}=(b_\theta-b_W)/(b_{TA}-b_W) \tag{5}$$

where b_θ, b_{TA} and b_W represent the work functions for the partly covered surface, completely covered surface, and pure tungsten respectively.

For approximate calculation of θ, Langmuir has also used the relation

$$\theta_{\mathrm{II}}=(\log I_\theta-\log I_W)/(\log I_{TA}-\log I_W) \tag{6}$$

where I_θ is the emission observed for the incompletely covered surface, I_W is the emission for pure tungsten, and I_{TA} is the emission for a surface completely covered with thorium.

Of these two methods for calculating θ, the first is the correct one from a theoretical point of view and should be used when values of the constant b_θ are available. On the other hand, Eq. (6) is very convenient to use in

practice, and usually leads to values of θ which are not very different from those obtained by use of the more rigorous equation.

The condition which has to be fulfilled in order that $\theta_I = \theta_{II}$ is easily determined as follows: Assume $I_\theta = A_\theta T^2 \epsilon^{-b_\theta/T}$ with similar relations involving A_{Th} and A_W for the fully activated and pure tungsten surfaces respectively. Then

$$\theta_I = \frac{\log(A_\theta/A_W) - \beta_\theta/T}{\log(A_{Th}/A_W) - \beta/T}$$

where $\beta = b_{Th} - b_W$ and $\beta_\theta = b_\theta - b_W$. But $\theta_{II} = \beta_\theta/\beta$; hence $\theta_I = \theta_{II}$ if

$$\frac{\beta_\theta}{\beta} = \frac{\log(A_\theta/A_W)}{\log(A_{Th}/A_W)}$$

i.e., if

$$\log A_\theta = \log A_W - \beta_\theta(\log A_W - \log A_{Th})/\beta \qquad (7)$$

That is, $\log A_\theta$ should be a *linear function* of β_θ. As will be shown, the experimental data do not lead to any such conclusion, and, therefore, the two definitions cannot be equivalent.

Emission Data on Partly Activated Surfaces

The most accurate series of data of this nature were taken with the tube K-364 described above. While emission data were also taken for different degrees of activation with tube K-363, they were not considered as very reliable. Firstly, for lower values of θ the emission at low temperatures decreased so much that with the instruments available no emission measurements could be obtained at temperatures below about 1300°–1400°K, while at higher temperatures (about 1650°K) the filaments begin to activate (that is, thorium diffusion begins to occur) at a rate, which, although very slow, is sufficiently great to interfere with accurate measurements. For pure tungsten itself, the lowest temperature at which emission data could be taken, with the instruments used, is about 1500°K. Therefore, it proved extremely difficult to obtain reliable emission data on deactivated surfaces for which θ approaches 0.20.

Table VII summarizes the results obtained with K-364 for different states of activation. The values of θ were calculated by means of Eq. (5) using the values $b_{Th} = 30{,}500$, $b_W = 52{,}400$.

TABLE VII

Results obtained with tube K-364 for different states of filament activation.

θ	A	b_θ	$\log_{10}A$
0.95	1.50	31,460	0.176
.83	2.08	34,150	.318
.72	3.74	36,570	.573
.56	7.76	40,070	.890
.43	10.86	42,840	1.037
.25	15.81	47,050	1.199
.18	(8.2)	48,360	.914

Plotting log A_θ against b_θ (see Fig. 3) it is observed that above a minimum value (corresponding to $b_\theta = 31{,}500$) four out of six points lie on a straight line passing through the value of log $A = 1.78$ which corresponds to pure tungsten. The values of A for $\theta = 0.25$ and $\theta = 0.18$ were obtained from data which were not nearly as reliable as those obtained for larger values of θ.

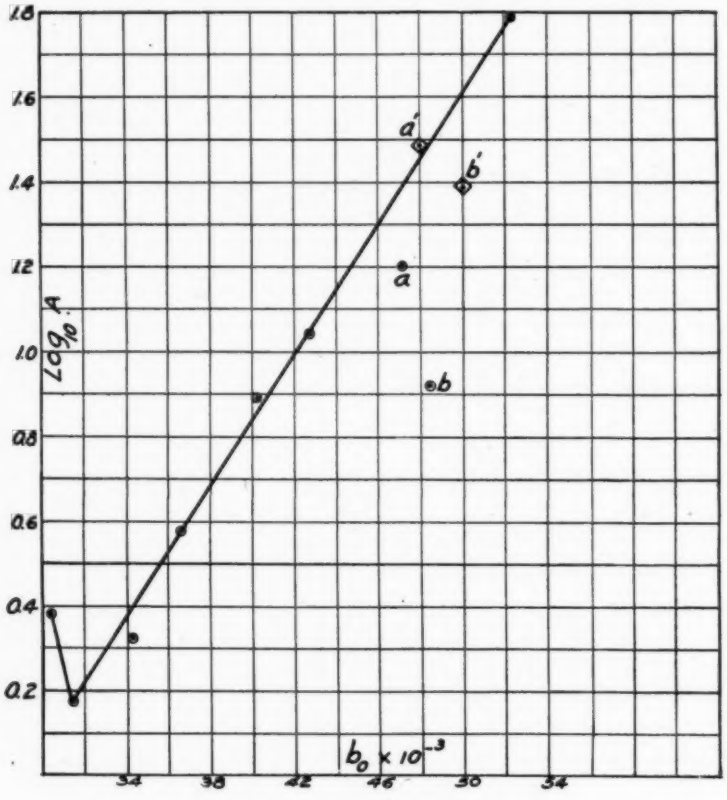


Fig. 3. Plot of log A_θ against b_θ.

In a discussion of these results with Dr. Kingdon, he suggested that a formula of the form

$$A_\theta = A_W(1-\theta)^n + A_{Th}\theta^n$$

might fit the observed data, since such an expression passes through a minimum value as θ is decreased. Empirically, it was found that $n = 2.5$ gives a better agreement with the observations than larger or smaller values of n, but it is even less satisfactory than the linear relation between log A_θ and b_θ suggested above.

One fact that must be considered is this, that a relatively small change in b_θ affects the value of A_θ a great deal. Thus, in the case of $b_\theta = 47{,}050$, if this value is decreased to $b_\theta = 48{,}000$, the resulting value of A_θ for constant emission at $T = 1500$, is found to be 29.8, which brings this point almost on the straight line.

Similarly for constant emission at $T=1500$, the values $A_\theta=24.6$ and $b_\theta=50{,}000$ correspond to $A_\theta=8.2$ and $b_\theta=48{,}360$. It should be stated that the emission data on which the latter values were based were taken over the range $T=1421$ to $T=1575$, which was undoubtedly too low a range for any great degree of accuracy.

From these considerations it would appear that the actual observations are not in disagreement with the tentative conclusion that from $\theta=0.95$ to $\theta=0$, $\log A$ varies linearly with b_θ (and therefore with θ).

Observations on other tubes, although not so accurate, were found to be in qualitative agreement with the observations discussed above in the conclusion that A_θ passes through a minimum value for a value of θ close to unity, as b_θ is increased.

Discussion of Results

In the earlier paper published by the writers,[1] the work function b_0 for a completely activated surface was given as 34,100. This was calculated on the assumption that $A=60.2$. However, it was observed that the actual slope of $\log (I/T^2)$ against $1/T$ gave consistently lower values of b and it was assumed that this was probably due to errors in temperature scale. Since then, Dr. Jones has completed his work on this problem and on the basis of his results the earlier emission data are found to be in very good agreement with the data given in this paper.

K. H. Kingdon[3] has also published emission data for thoriated tungsten, for both the completely activated and incompletely activated surfaces. Using the guard ring principle he obtains for $\theta=1$, the values $A=7$, $b_0=31{,}200$ (at anode potential of 150 volts), and for partly activated surfaces, the relation

$$A_\theta=(7^\theta+60^{1-\theta}-1)\ \text{amps/(cm}^2\text{deg.}^2\text{)}$$

Values of θ were calculated from observed values of b_θ by means of Eq. (5).

The filament temperatures were determined from the heating current and Dr. Kingdon believes that the accuracy of his temperature determination was therefore not as great as that obtained in the present investigation. At $T=1000$, the emission calculated on the basis of Kingdon's constants is practically identical with that given in Table IV, while at $T=1500$, Kingdon's constants lead to a value 50 percent greater, which is probably to be accounted for by two sources of error: (1) failure to correct for effect of anode voltage, and (2) difference of about 1 percent in temperature at the upper point of his working range.

Kingdon's observations on the variation of A_θ with b_θ are in qualitative agreement with those obtained in the present work, but there is a lack of quantitative agreement.

Interpretation of Observed Value of A for Completely Covered Film of Thorium on Tungsten

Careful measurements on tungsten, molybdenum and tantalum in this laboratory, as well as similar measurements by Germer and Davisson on

tungsten and by C. Zwikker[8] on tungsten and thorium lead to the conclusion that for at least these four metals the constant A has the value 60.2 (within the probable limits of error in determination of temperatures).

The writers believe that this conclusion is probably valid for all pure metals (subject to slight differences due to effect of surface charge, as pointed out by Bridgman[9]). On the other hand, the present observations for the case of monatomic layers of thorium on tungsten, Kingdon's measurements for caesium on tungsten, and the results obtained for Wehnelt cathodes show that for these surfaces A is less than 60.2.

It is of interest in this connection to point out that while A is less than 60.2 for a monatomic layer of thorium on tungsten, the value of b for the monatomic layer is less than that for metallic thorium, as is evidenced by the published data of Zwikker and is also confirmed by recent measurements in this laboratory on some thorium wire kindly provided by Dr. Myers of the Research Laboratory of the Westinghouse Company.

Also some recent measurements in this laboratory on monatomic layers of zirconium on tungsten[10] show that in this case $A=5$ and $b_0=36{,}500$, while for metallic zirconium Zwikker gives the values $A=3000$, $b_0=52{,}200$. Thus the emission over the range of working temperatures is lower for metallic zirconium than for the film.

There is, therefore, every reason for believing that for all cases where we have a monatomic layer of a more electropositive metal on another metal, the value of A is less than 60.2. On the other hand, for surfaces more or less partly covered with oxygen, A is greater than this value, and the same conclusion apparently holds true in all cases where we have a monatomic layer of a more electronegative element, as, for instance, phosphorus or iodine on tungsten.[11]

The significance of these deviations in the value of A from the so-called constant value is probably to be found in a consideration of Bridgman's theory of the effect of surface charges and of the validity of the third law for monatomic films. The discussion of this subject must, however, be deferred for further consideration in a paper by Dr. L. Tonks and the first named writer, which will appear in the near future.

RESEARCH LABORATORY,
GENERAL ELECTRIC COMPANY,
December 31, 1926.

[8] C. Zwikker, Proc. Royal Academ. Amsterdam **29**, 792 (1926).
[9] P. Bridgman, Phys. Rev. **14**, 306 (1909).
[10] To be published in the near future.
[11] As shown by observations made by the writers.

NEUTRALIZATION OF THE DEFLECTING FIELD IN A BRAUN TUBE WITH EXTERNAL ELECTRODES

By L. T. Jones and A. M. Cravath

Abstract

The field of the external electrodes is rapidly neutralized by the collection of ions and electrons on the tube walls so that the deflection is not simply proportional to the applied voltage. The neutralization proceeds like the discharge of a condenser through a resistance for which the time constant is $RC=\tau$. This time constant τ, which is a reciprocal measure of the rate of neutralization, was calculated from current measurements made with internal electrodes together with the dimensions of the tube, and was also measured directly by photographing the variation of deflection with time, the respective values for a certain tube being 0.002 sec. calculated, and from 0.001 to 0.005 sec. measured under different conditions. The deflection of the beam is found as a function of τ and the applied voltage, and in particular the expressions for amplitude and phase of deflection for sinusoidal applied voltage are derived, the results being

$$D = V_0 S \cos\delta \sin(2\pi f t + \delta)$$

$$\delta = \cot^{-1} 2\pi f \tau$$

where D is beam deflection, V_0 the applied voltage, f the frequency, and S is a constant of the tube.

1. Introduction

THE present paper deals with a problem which arose in the investigation of Jones and Tasker[1] on the Braun tube with external electrodes, namely, the determination and explanation of the relation between deflection of the beam, and the applied voltage and time. The type of tube used is shown in Figures 1 and 5, and its functioning is described in the previous paper.

When a potential difference is suddenly applied to the external electrodes, the beam is of course deflected at first, but the electrons returning from the end of the tube are drawn to the wall next the positive electrode and the positive mercury ions formed by collision with the mercury vapor atoms are drawn to the wall next the negative electrode. The field inside the tube is thus rapidly neutralized and soon becomes zero. Neutralization also occurs when an alternating voltage is applied, the result being a change in phase and amplitude.

A quantitative theory for the latter case was developed in this laboratory in an unpublished paper by R. A. Jack. In the present paper the theory is modified and generalized and checked by comparing the neutralizing current of ions and electrons necessary to give the observed neutralization with the observed current between large internal electrodes in a tube otherwise similar.

[1] Jones, and Tasker, Jour. Opt. Soc. Am. 9, 471 (1924).

2. Theoretical Development of Equations for the Deflection

If, leaving other things unchanged, we were to silver the parts of the inner surface of the walls of the tube which lie between the external electrodes, thus obtaining insulated internal electrodes, the collection of ions and electrons on the tube walls would not be changed on the average, but would merely be somewhat differently distributed because of the more uniform potential distribution. We shall therefore treat the problem as if there exists such a pair of internal electrodes, B_1 and B_2, between the external electrodes A_1 and A_2. B_1 and B_2 are charged inductively from A_1 and A_2 and then discharged by the current of ions and electrons. We shall make the further assumption, to be discussed later, that this ion-and-electron neutralization current is proportional to the potential difference V between B_1 and B_2, i.e., that the ions and electrons act like a high resistance R connected between B_1 and B_2 Since the beam deflection is proportional to the potential difference between the walls, our problem is to find this potential difference V. In the general electrostatic equations

$$\left.\begin{aligned} V_{B1} &= p_{B1B1}Q_{B1}+p_{B1B2}Q_{B2}+p_{B1A1}Q_{A1}+p_{B1A2}Q_{A2} \\ V_{B2} &= p_{B2B1}Q_{B1}+p_{B2B2}Q_{B2}+p_{B2A1}Q_{A1}+p_{B2A2}Q_{A2} \\ V_{A1} &= p_{A1B1}Q_{B1}+p_{A1B2}Q_{B2}+p_{A1A1}Q_{A1}+p_{A1A2}Q_{A2} \\ V_{A2} &= p_{A2B1}Q_{B1}+p_{A2B2}Q_{B2}+p_{A2A1}Q_{A1}+p_{A2A2}Q_{A2} \end{aligned}\right\} \quad (1)$$

V_{B1} is the potential of B_1, etc., the p's are the potential coefficients, constants of the tube, and the Q's are the quantities of electricity. In general $p_{\alpha\beta}=p_{\beta\alpha}$. From this and the symmetry of the apparatus we have:

$$\left.\begin{aligned} &p_{A1B2}=p_{B2A1}=p_{A2B1}=p_{B1A2} \\ &p_{A1B1}=p_{B1A1}=p_{A2B2}=p_{B2A2} \\ &p_{A1A2}=p_{A2A1},\quad p_{B1B2}=p_{B2B1} \\ &p_{A1A1}=p_{A2A2},\quad p_{B1B1}=p_{B2B2} \end{aligned}\right\} \quad (2)$$

The above equations give

$$V=V_{B1}-V_{B2}=(Q_{B1}-Q_{B2})\left\{p_{B1B1}-p_{B1B2}-(p_{B1A1}-p_{B1A2})^2/(p_{A1A1}-p_{A1A2})\right\}$$
$$+(V_{A1}-V_{A2})(p_{B1A1}-p_{B1A2})/(p_{A1A1}-p_{A1A2})=(Q+V_aC_a)/C_b \quad (3)$$

where $Q=\frac{1}{2}(Q_{B1}-Q_{B2})$ is the quantity of electricity transferred in neutralization, V_a is the potential difference applied to the external electrodes, and C_a and C_b are constants. To determine the significance of C_a, suppose B_1 and B_2 to be connected. Then $V=0$, and

$$C_a=-Q/V_a$$

Hence we see that C_a is the ratio of the charge induced on the electrodes B_1 and B_2 to the inducing potential difference applied to the electrodes A_1 and A_2. Next, short-circuit A_1 and A_2, making $V_a=0$. Then

$$C_b=Q/V$$

and we see that C_b is the capacity between B_1 and B_2 when A_1 and A_2 are connected together.

Differentiating Eq. (3) with respect to time gives

$$\frac{dV}{dt}=\frac{C_a dV_a/dt+i}{C_b}$$

We have assumed

$$i=-V/R$$

where the minus sign appears because the positive direction of i is the direction which gives positive Q_{B1} and is hence against the field. The equation now becomes

$$\frac{dV}{dt}=\frac{C_a dV_a/dt-V/R}{C_b}$$

for which the solution is

$$V=\frac{C_a}{C_b}e^{-t/RC_b}\left(\int e^{t/RC_b}\frac{dV_a}{dt}dt+\text{const.}\right) \tag{4}$$

We see that the characteristics of the tube enter in two terms, the constants C_a/C_b, and RC_b. The first, C_a/C_b, depends on the dimensions and positions of the electrodes, and merely affects the scale of the deflections. The more important term is the second, RC_b, which influences the variation of deflection with time. It is the time constant for the exponential discharge of B_1 and B_2 through R when A_1 and A_2 are short circuited. We shall call it the time constant of the tube and designate it by τ. Since the deflection of the beam, D, is proportional to V, (4) gives

$$D=Se^{-t/\tau}\left(\int e^{t/\tau}\frac{dV_a}{dt}dt+\text{const.}\right) \tag{5}$$

where S is a constant. This is the general equation for the deflection in terms of the applied voltage and time.

The deflection was photographed. The deflecting voltage V_a was that across a condenser of capacity C_1 which was being charged and discharged through a resistance R_1, the time constant being $C_1R_1=\kappa$. For these cases

$$V_a=V_0(1-e^{-t/\kappa}) \quad \text{and} \quad V_a=V_0e^{-t/\kappa}$$

For both charge and discharge Eq. (5) now gives

$$D=\{SV_0/(\kappa/\tau-1)\}(e^{-t/\kappa}-e^{-t/\tau}) \tag{6}$$

the only difference between the two cases being a reversal of the direction of deflection. The simple case of an instantaneously applied or removed constant voltage is obtained by making $\kappa=0$. Eq. (6) then reduces to the simple exponential decay

$$D=SV_0e^{-t/\tau} \tag{7}$$

If the applied voltage is sinusoidal, i.e., $V_a = V_0 \sin \omega t$, Eq. (5) gives

$$D = \{V_0 S\tau\omega/(1+\tau^2\omega^2)^{1/2}\} \sin(\omega t + \cot^{-1}\tau\omega) \quad (8)$$
$$= V_0 S \cos\delta \sin(\omega t + \delta)$$

where $\delta = \cot^{-1}\omega\tau$ is the angle by which the deflection *leads* the applied voltage.

The above theory was checked in two ways: first, by comparing the shape of photographic deflection curves with the shape of the curves predicted by the above equations, and secondly by the more significant method of comparing the value of τ found from the observed deflection with the value calculated from R and C_b. The determination of R requires the measurement of the neutralizing current for known potential difference between the walls.

3. Measurements of Neutralizing Current

To find R we used special tubes, Fig. 1, and measured the currents between large internal electrodes about 3×10 cm spaced 1.3 cm apart which took the place of the tube walls or "electrodes" B_1 and B_2 of the tube with

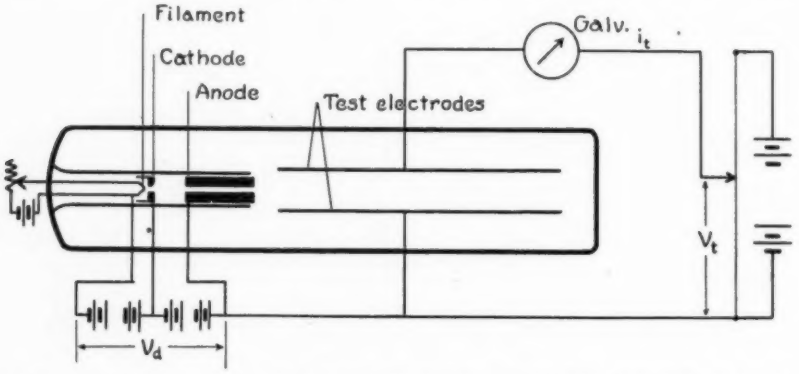


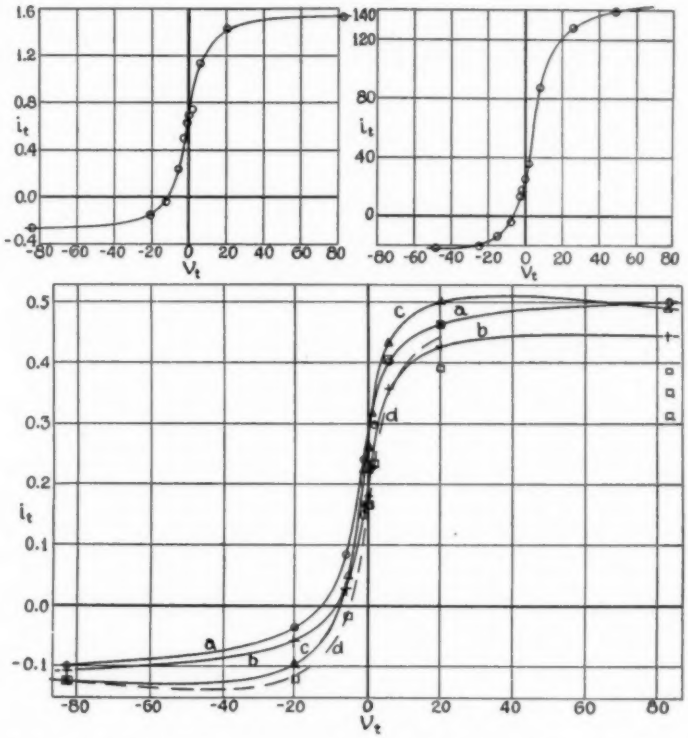
Fig. 1. Tube and connections for current measurements with internal electrodes.

external electrodes. The filaments, cathodes, anodes, and atmospheres in these tubes were the same as in the tube with external electrodes except that tube No. 1 had a slow leak and was fitted with a side tube containing thorium which could be heated to renew the vacuum.

Figs. 2, 3, and 4 show the galvanometer current i_t as a function of the potential difference between the electrodes V_t. The four curves of Fig. 4 were obtained to show the effect of varying the accelerating voltage, V_a. The absolute values of V_a were not accurately measured, but the differences are reliable. Fig. 3 taken with tube No. 2 shows the effect of increasing the beam current 250 times relative to Fig. 4. We see that practically the only difference between the various curves is in the scale of ordinates. At a given voltage they all show about the same fraction of the saturation current.

Equal and like quantities of electricity on each of the opposite walls of a tube with external electrodes would not produce any potential difference and hence would not affect the beam deflection. Rate of neutralization is

proportional to the *difference* between the currents to the opposite walls. When $V_t=0$, each electrode receives half the return electron current from the beam, and the neutralization current is zero. The neutralizing current is therefore $i_t-i_{t_0}$ where i_{t_0} is the value of i_t when $V_t=0$. For large V_t it approaches a saturation value which ranges from 3×10^{-7} amperes for tube No. 1 with a beam so faint as to be just visible in a daylighted room to 7×10^{-5} amperes for tube No. 2 which had a very bright beam. About 7



Figs. 2, 3, and 4. i_t, the current to test electrodes in microamperes, as a function of V_t, the voltage between test electrodes.

	Fig. 2	Fig. 3	Fig. 4a	Fig. 4b	Fig. 4c	Fig. 4d
Tube No.:	1	2	1	1	1	1
Accelerating voltage V_d.:	740	445	750	600	400	300
Beam current i_b in microamperes:	1.2	120	0.4	0.33	0.38	
Resistance to neutralization in megohms:	10	0.12	26	30	26	33
Positive ions per beam electron:	0.21	0.17	0.25	0.32	0.33	0.4

volts, or 5 volts per cm, gives half the saturation current. For small values of V_t the neutralizing current is proportional to the potential difference and we can obtain R, the resistance to neutralizing current, from the initial slopes of the curves. The values are given with the curves. R is found to be inversely proportional to the beam current as might be expected, the values of Ri_b (ohms$\times$amperes) being 12, 11, and 15 for curves 2, 3, and 4a. When the deflections with external electrodes were being observed, the transverse fields

between the walls rose considerably above the range for which the current is proportional to field. Our assumption of a constant R which was used in developing the equations for deflection therefore leads to results that are little more than qualitative.

The distance between the walls of the tube used in measuring the deflections with external electrodes (Fig 5) averaged about four times the distance between the electrodes of the tubes used for the current measurements. If in these tubes the same field produces the same neutralizing current, the potential differences and resistances will have the ratio four, and for the tube used in measuring deflection

$$R=(12/i_b)\times 4=50/i_b$$

From the dimensions and material we find

$$C_b=10^{-10}\text{ farads.}$$

hence

$$\tau=RC_b=50\times 10^{-10}/i_b$$

If we put i_b in microamperes and τ in thousandths of a second, then $\tau i_b=5$.

The approximate number of positive ions formed by each beam electron can also be determined from the curves. The galvanometer current i_t is made up of two parts: the electrons originally in the beam which have struck the end of the tube and are returning, and the electrons and positive ions formed by collision with gas molecules. When V_t is positive and large enough for saturation, all of the original electrons of the beam and in addition all the electrons formed by collision are drawn through the galvanometer. For large negative V_t, only the positive ions are drawn through the galvanometer, and the saturation current gives their number. This is also the number of electrons produced by collision. Therefore subtracting the saturation current for negative V_t from that for positive V_t gives immediately the total beam current. This has been checked independently. Hence the number of positive ions formed per beam electron is simply the ratio of the positive saturation current to the difference between the two saturation currents. The values, given with the curves, lie between 0.4 and 0.17, showing that neutralization is principally due to the original electrons of the beam rather than to new ions and electrons produced by collision. The data of Compton and Van Voorhis[2] on probability of ionization by electron impact would give 0.18 ions per electron in these tubes for 350 volt electrons, but they do not extend to the higher velocities with which most of the present measurements were made.

4. Measurements of Deflection with External Electrodes

The tube, electrical connections, and photographic arrangement used are shown in Fig. 5. The beam current i_b was measured by closing the galvanometer switch which was open during deflection observations.

[2] Compton and Van Voorhis, Phys. Rev. **26**, 436 (1925).

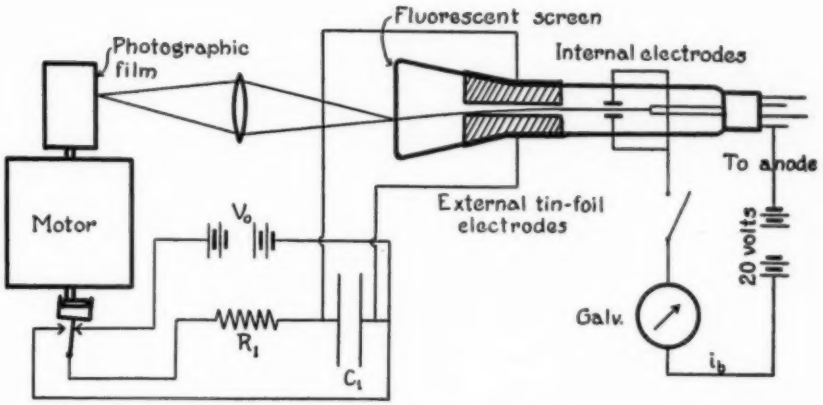


Fig. 5. Tube and connections used for deflection measurements.

In the simple case $R_1=0$ a constant voltage V_0 is suddenly applied and removed. Fig. 6 is an example of the deflection obtained. Here Eq. (7) applies and τ can be calculated from the deflections at two different times,

$$\tau=\frac{t_2-t_1}{\ln D_1/D_2}$$

In comparing different curves where i_b varies, τi_b should be constant since

Fig. 6. Deflection produced by suddenly applying and removing voltage on external electrodes.

we found Ri_b constant. The results are given in Table I. The average agrees with the value calculated from the current measurements, and we see here

Fig. 7. Deflection when external electrodes are connected to a condenser which is alternately charged and discharged through a resistance. Dashed curve is calculated.

the same approach to saturation that we found in the current measurements; the values of τ increase with increasing field and deflection. Moreover, the

two branches of the curves, caused respectively by application and removal of the voltage, give different values of τ, the difference being specially great when V_0 is large. A similar asymmetry is noticeable in the curves taken with $R_1 \neq 0$, e.g., Fig. 7, and is sometimes observed with sinusoidal applied voltage. It is due to the fact that one electrode is maintained at a fairly constant potential while the other varies. When the latter becomes suddenly more positive, electrons are attracted to the wall next it and neutralization is rapid. When it suddenly becomes more negative, the electrons are repelled toward the anode or "plate" through which the beam emerges, and the

TABLE I

Showing the values of τ obtained in different ways. The values or sets of values for each film refer to the two branches. The times τ and t_1 and t_2 are given in thousandths of seconds. The current i_t is given in microamperes.

From the rate of decrease of deflection after sudden application or removal of constant voltage V_0						From the magnitude of maximum deflection				
τ	τi_t	t_1	t_2	*Film*	V_0	τ	τi_t	Film	V_0	R_1
4.62	15	4.4	7.5	#12	220	1.93	3.69	#2	45	500
3.57	11.7	7.5	10			0.91	1.75			
2.75	9.0	10	12.7							
						1.43	2.94	#3	95	300
2.40	7.85	2.5	4.6			1.02	2.10			
1.66	5.42	4.6	6.0							
1.36	4.44	6.0	7.4			3.45	6.55	#5	220	5000
						1.28	2.44			
2.3	6.10	0.0	0.44	#4	70					
0.99	2.62	0.44	1.32	(Fig. 6)		5.48	10.2	#6	220	7000
1.68	4.45	1.32	3.30			1.76	3.34	(Fig. 7)		
1.83	4.85	0.00	0.38			1.1	2.6	From the magnitude of deflection with 60 cycles		
1.16	3.07	0.38	1.1							
1.17	3.10	1.1	2.0							
						2.0	5.0	Calculated from measured neutralization current		

relatively few positive ions which are attracted give a relatively slow neutralization.

Fig. 7 is an example of the deflection obtained when both capacity and resistance are in circuit. The dotted curve is that given by Eq. (6). The constant S was found from the initial deflection of Fig. 6, $D = V_0 S$. R_1 was known. The value of C_1 used was the average calculated from the initial slopes of all similar curves. τ was found from the maxima. The results for all curves obtained are given in Table I.

The magnitude of the deflection produced by a 60-cycle sinusoidal voltage was measured and τ was calculated from Eq. (8). The result, also given in Table I, agrees with the other values.

CONCLUSION

Current measurements with large internal metal electrodes show that the electron and ion current has the order of magnitude and variation with

field that is necessary to explain the deflections observed with external electrodes. For small applied voltages, the tube acts as if the inner surfaces of the walls between the external plates were electrodes connected through a resistance which is inversely proportional to the beam current.

Neutralization is principally due to the original electrons of the beam which have struck the end of the tube and are returning, rather than to new ions and electrons produced by collision.

DEPARTMENT OF PHYSICS,
UNIVERSITY OF CALIFORNIA.
January 5, 1927

THE INDEX OF REFRACTION OF WATER FOR SHORT CONTINUOUS WAVES

By L. E. McCarty and L. T. Jones

Abstract

The index of refraction of water for short continuous waves (300 to 700 cm) was measured from the phase difference resulting between two portions of a wave, one portion of which had passed through the dielectric. The phase difference was detected and measured by the rotation of the Lissajous figure, formed on the screen of a cathode ray oscillograph, due to the simultaneous action on the cathode beam of two tuned circuits receiving the two portions of the wave. The two circuits were attached to the opposite pairs of deflector plates of the oscillograph. The index of refraction was calculated from the relation $\mu = m\lambda/d + 1$, where λ is the wave-length, d the thickness of interventing dielectric in one path, and m the fraction of a period by which the wave passing through the dielectric is retarded relative to the one passing through air. The results are in good agreement with the electrical refractive index found by other methods, i.e., about 9, and approximately constant over the range of frequencies used. Brief reference is made to a method by which it is hoped to measure the dielectric constant under conditions identical with those existing in the measurement of the index of refraction, to be used in conjunction with the latter, in testing Maxwell's relation between index of refraction and dielectric constant.

THE work described in this paper represents the first part of an experimental test of Maxwell's relation between refractive index and dielectric constant, $K = \mu^2$, especially for such substances as water and alcohol, for which a very great discrepancy has been observed, and under more nearly identical conditions than have obtained in previous experiments. Inasmuch as most of the earlier tests of the relation were based on values of the refractive index and dielectric constant measured at vastly different frequencies and sometimes at different temperatures, it was not to be expected that verification would be complete. Both refractive index and dielectric constant depend on frequency and temperature. Numerous investigations extending from about 1895 to the present time have shown that the discrepancies are much reduced when the quantities to be compared are measured under more nearly similar conditions.[1] P. Drude[2] measured the reduction in wave-length suffered by short damped electromagnetic waves (40 to 600 cms) on passing from air to water along a Lecher Wire system, and obtained about 9 for the electrical refractive index of water, a result in very close agreement with the theory. This result has been confirmed by many others using various methods, and wave-lengths varying from a few millimeters to several meters. The importance of the temperature factor was shown by the experiments of

[1] See Fleming and Dewar, Proc. Roy. Soc. Lond. **61**, 2 (1897) for a summary of the work done before 1897.

[2] P. Drude, Wied. Ann. **54**, 352–370 (1895); **55**, 633–655 (1895); **58**, 1–20 (1896).

Dewar and Fleming just referred to. In view of this close dependence of index of refraction and dielectric constant on frequency and temperature it appears that in order to have a fair and decisive test of Maxwell's relation the two quantities involved must be measured under absolutely identical conditions; and the purpose of this experiment, therefore, was to measure in a single experiment, under conditions as nearly identical as possible, the two quantities entering into Maxwell's relation. The only part of this plan which has been carried out so far is the development of the method and its application to the measurement of the refractive index of water at a few frequencies of the order of 10^8 cycles per second. The results so far obtained are in agreement with those already found.

In this method the refractive index is computed directly from the phase difference introduced between two portions of a wave by the retardation of one portion in passing through the dielectric. The two parts of the wave were picked up by two tuned circuits attached to the opposite pairs of deflector plates of a cathode ray oscillograph, and the phase difference measured from the rotation of the resulting Lissajous figure. The arrangement of apparatus is shown in the accompanying diagram, Fig. 1.

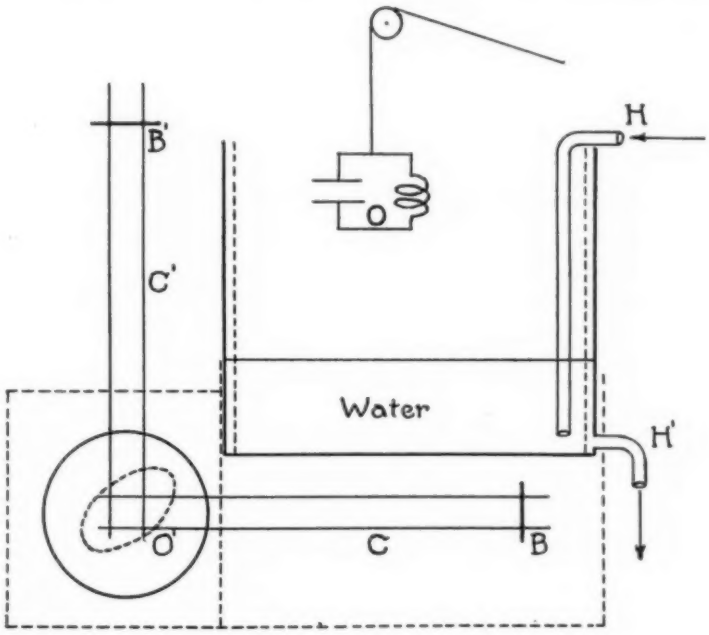


Fig. 1. Schematic diagram of apparatus.

O is a simple vacuum tube oscillating circuit (5 to 7.5 watts) suitable for generating short waves. It was suspended from a pulley over a glass water tank of dimensions $1 \times 0.5 \times 0.5$ meters. By means of the hose H and H' the depth of water could be varied continuously. The circuits C and C' received the waves traversing the water and air paths, respectively, and the

two alternating electromotive forces induced in the circuits acted simultaneously, at right angles, on the electron beam causing it to trace an ellipse on the oscillograph screen O′. The shape of the ellipse depends on the amplitudes and phase difference of the two impressed e.m.f.'s. The oscillograph, was of the ordinary type[3] with internal deflector plates. The oscillograph was enclosed by a screen of iron wire of 0.5 inch mesh, and circuit *C* was screened from all directions except the side next the water with 1/8 inch iron screen. A lens and film holder were placed in front of the oscillograph. The wave-lengths were measured on a Lecher bridge system in the usual manner.

The procedure followed in taking a series of observations or photographs, such as that shown in Fig. 2, was somewhat as follows: A thin layer of water was run into the tank to correct for the capacity effect of the water on

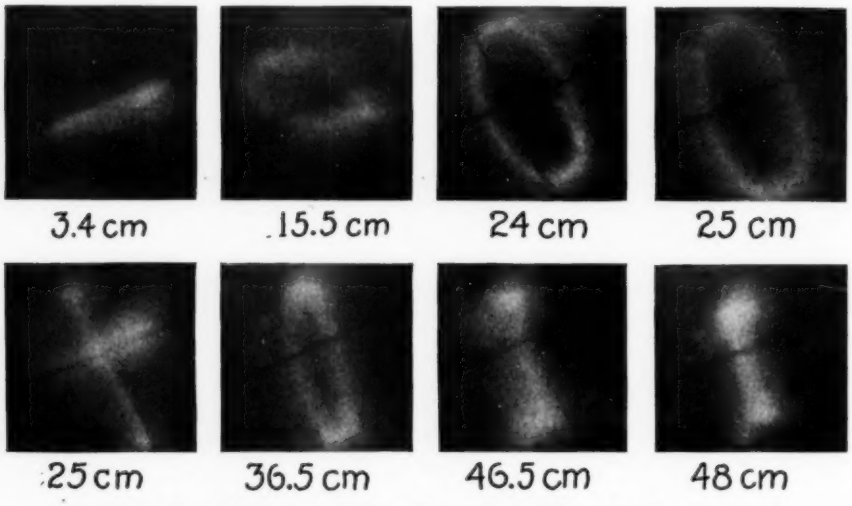


Fig. 2. Photographs of Lissajous figures for various depths of water.

circuit *C*. The circuits were then tuned by means of the adjustable bridges *B* and *B′* until they gave a convenient sized figure on the oscillograph screen. If the figure was not approximately a straight line it was usually made so by slight adjustment in the position of the oscillator, thickness of water layer or by changing the inductance in circuit *C′*. The hydrant was then opened, water run into the tank, and the various phases of the ellipse photographed, and the corresponding depths of water read. Similar sets of observations were made with the water flowing out. The water flow was stopped during an exposure. The figures below the photographs in Fig. 2 represent the depth of water at which the phase occurred. The fifth exposure is a double exposure showing the direction and amplitude of each vibration separately. The directions of vibration remained constant, but the amplitudes varied in the different exposures. On account of the time required to make a series

[3] Jones & Tasker, J.O.S.A. 9, 471 (1924).

of exposures and the mishaps which often occurred during an unusually long run, it was found that more and better data could be secured by simply observing and recording a number of values of the depth, with the water alternately rising and falling, corresponding to certain definite forms of the figure (straight line or maximum ellipse) which were used in the computations. Two such series of readings are given in Table I. The first two

TABLE I

Containing recorded thickness of dielectric corresponding to the straight line position shown in Fig. 2 for $\lambda = 702$ *cm.*

Lower straight line position		Upper straight line position	
Water Flowing in Depth cm	Water Flowing out Depth cm	Water Flowing in Depth cm	Water Flowing out Depth cm
	Phase change 180°.		
3.5	4.0	47.0	46.9
3.4	3.0	47.1	48.0
3.4	3.5	47.9	47.2
2.8	3.1	47.0	48.2
3.6	3.3	48.0	47.6
3.8	4.0	48.0	48.0
4.1	3.6	(Tank overflowed)	
3.9	3.3		
4.1	3.3		
Aver. 3.26	3.11	47.50	47.67
Final Aver. 3.18		47.58	
	$d = 44.4$cm $m = 0.5$	$\mu = 8.9$	
	Phase change 90°		
1.2	1.5	23.0	22.5
1.3	1.8	23.1	22.8
.8	1.0	23.0	23.0
.5	1.0	23.1	23.2
1.0	1.5	23.0	22.8
1.0	1.0	23.0	23.2
.9	1.1	22.9	22.7
1.2	.9	22.9	23.0
.8	.9	23.0	22.6
.7	.6	23.1	22.8
Aver. 9.4	1.13	23.01	22.86
Final Aver 1.04		22.90	
	$d = 21.9$ cm $m = 0.25$	$\mu = 9.0$	

columns of the first set give depths of water read as the figure passed through a straight line position in one quadrant and the last two give the depths read as it passed a straight line position in an adjacent quadrant. The readings in the second set have a similar meaning except that the last two columns were taken as the figure passed through the maximum ellipse. The depths in the first and third columns of each set were read with water flowing into the tank, the second and fourth columns with water flowing out. The readings in adjacent columns were taken alternately in pairs.

Before presenting the results it will be necessary to refer to certain practical difficulties encountered in connection with screening and measurement of the rotations, and to explain how they were surmounted. It was soon

apparent that other factors besides changes in phase difference were operating to produce peculiar irregularities in the rotation of the ellipse. Investigation showed that they were due to irregular variations in amplitude of the vibrations, caused apparently, by such effects as resonance, reflection and standing waves, mutual interactions between the circuits, and absorption. All the irregularities were not accounted for and it seemed impossible to eliminate or to correct for them by analysis of the rotations. For this reason it was decided to avoid their effects altogether by basing the calculations on phase changes which were caused by multiples of 90° rotations, and in most cases on changes from a straight line position in one quadrant to a straight line in an adjacent quadrant. An analysis of the pseudo-rotations caused by amplitude changes alone shows, first, that the rotation is always confined to a single quadrant, and, second that it cannot cause a change of shape of the figure from a straight line to an ellipse, or vice versa. In case an ellipse degenerates into a straight line as a result of one of the component amplitudes becoming zero, this line will always lie along one of the axes. Hence it is at least safe to assume that the rotation between straight line positions in adjacent quadrants is due to phase change alone regardless of any irregularities in between, which may be due to both causes; and it is fairly certain that a change from a straight line position not along an axis to a maximum ellipse, or circle, is caused by a phase change of 90°. This point is illustrated, though not nearly so well as in many other observed cases, by the series of photographs in Fig. 2. In the first place it is obvious from these photographs that the amplitudes of the vibration in both circuits has changed, that in circuit C' having been reduced as the depth of water increased while that in C increased. These photographs also indicate an actual rotation of the axes of the figure through slightly more or less than 90°, depending on whether the rotation is considered as clockwise or counter-clockwise. It seemed to be clockwise. The first approximate straight line position, corresponding to 3.4 cms of water, appears to be nearly in the line with one of the axes, but the subsequent changes and the other straight line position could not well be explained by amplitude changes alone. Besides, the observations, which were more complete and accurate, showed that the best value of the lower position corresponded to 3.18 cm and was more inclined to the direction of vibration produced by C'. The results in Table 2, with the one exception noted, were computed from consecutive straight line positions in adjacent quadrants, assumed to be due to 180° phase changes in circuit C.

The equation giving the relation between index of refraction, phase difference, wave-length, and thickness of dielectric is derived as follows: Let t_1 be the time required for the wave to pass from the source to the detector by the air-path, a distance D cm, and t_2 the time required to pass through the dielectric of thickness d cms and a distance $D-d$ cms of air-path.

Then $t_1 = D/c$, and $t_2 = \mu d/c + (D-d)/c$ where c is the velocity of the wave in air. Also

$$t_2 - t_1 = d(\mu - 1)/c$$

But $t_2-t_1=mT$, where T is the period (λ/c) and m is the fraction of a cycle of phase difference introduced. Then

$$\mu=m\lambda/d+1$$

As previously stated the wave-length λ was measured by means of a Lecher system. A crystal and milliammeter or a vacuum thermocouple was used to indicate the position of the nodes. The thickness of dielectric d required to make $m=\frac{1}{2}$ was read directly from a meter bar standing against the inside wall of the tank. The method of computing the average values of d for $\lambda=702$ cm is indicated in Table I, also the substitutions and calculation of μ for this wave-length. The other values of μ shown in Table II were

TABLE II

Showing measured values of λ m and d with corresponding values of μ.

λ cm	m	d cm	μ
702	$\frac{1}{4}$	21.9	9.0
	$\frac{1}{2}$	44.4	8.9
670	$\frac{1}{2}$	45.3	8.4
500	$\frac{1}{2}$	31.6	8.9
496	$\frac{1}{2}$	29.8	9.3
425	$\frac{1}{2}$	27.2	8.8
384	$\frac{1}{2}$	22.7	9.4
332	$\frac{1}{2}$	20.0	9.3

computed in a similar manner except that the amount of data used for the two shortest waves was less than for the longer waves. The small size of the ellipse made it very difficult to obtain accurate data at the short wave-lengths.

The values of μ for the different wave lengths used are seen in Table II to be almost constant and in substantial agreement with those obtained by others with different methods. The degree of accuracy of the experiment does not warrant any conclusions as to the slight variations shown. The indistinctness referred to by J. B. Johnson,[4] due to the time required for the beam to produce the ionization necessary for focusing, did not cause trouble as had been feared. There was some erratic behavior of the spot at certain times at all frequencies, but it did not appear to be any worse at frequencies of 10^8 than at 10^6 where haziness was observed by Johnson. The difficulty experienced in making observations at the shortest wave-lengths appeared to be due to the small size of the figures, resulting from lack of sufficient power at these high frequencies, rather than to haziness caused by incomplete focusing. The broadening of the figure in some of the photographs shown was due to a division of the beam into two parts, apparently two points of emission at the filament.

It is planned to make a direct measurement of dielectric constant at exactly this same frequency and temperature by substitution of a part of the same specimens used in the refractive index determination between the plates of

[4] J. B. Johnson, J.O.S.A. **6**, 701 (1922).

the variable air condenser in the oscillating circuit and noting the distance of separation of the plates required to tune it back to the original wave-length as indicated by resonance with the same length of the Lecher system. This is a slight modification of the method described in Bulletin No. 74 of the U. S. Bureau of Standards. A rough preliminary trial has been made but no reliable results have yet been obtained.

In order to apply this method to other dielectrics with smaller indices of refraction, it will be necessary to make certain refinements and to eliminate some of the causes leading to irregular changes in amplitude so that small phase changes may be detected. It should be possible to detect and measure fairly small rotations by a null method, i.e. by bringing the figure back to its original position.

DEPARTMENT OF PHYSICS,
UNIVERSITY OF CALIFORNIA.
February 24, 1927.

THE HIGH FREQUENCY RESISTANCE OF A BUREAU OF STANDARDS TYPE VARIABLE AIR CONDENSER

By S. L. Brown, C. F. Wiebusch and M. Y. Colby.

Abstract

A method is described whereby the high frequency resistance of variable air condensers is measured with an accuracy of one percent. Data are given showing the resistance of a Bureau of Standards Type 0.0035 $\mu\mu f$ condenser at wave-lengths from 40 to 175 meters and at different positions on the scale. The values obtained range from 0.0283 ohms at 119 meters and 174° scale setting (range 0° to 180°), to 0.150 ohms at 63 meters and 20° condenser setting. The resistance increases rapidly towards the lower positions on the scale, and also increases with wave-length.

Experimental check of the calculated values of the high frequency resistance of large conductors:—The resistance of single turn coils of B and S No. 8, 2, 00, and 0000 annealed copper wire were measured at wave-lengths from 40 to 175 meters. These values were compared with the calculated values and were found to check to within two percent in most cases and the discrepancies may easily be ascribed to experimental errors.

IT HAS been considered quite permissible by many writers either wholly to neglect, or to use an approximate value for, the high frequency resistance of low-loss air condensers, in comparison with the total resistance of the circuit in which they were included. It is the purpose of this paper to show that, in cases where the total resistance of the circuit is low, not only the resistance of the condenser, but also its variation with frequency and setting must be taken into account.

The plan followed in the investigation made was to measure the total resistance of a tuned circuit in which the condenser was included and then separate the condenser resistance from that of the remainder of the circuit. The resistance variation method so frequently used for measuring the resistance of tuned circuits does not give, without modification, sufficiently accurate results in low resistance circuits. In order to obtain reliable values for the condenser resistance by this method the resistance of the remainder of the circuit should be as small as possible; otherwise the condenser resistance may be entirely concealed by experimental errors in the value of the total resistance. But this condition cannot be realized as long as it is necessary to include the resistance of an ammeter in the circuit. Furthermore, in previous descriptions[1] of the use of this method for determining the total resistance of the circuit, the separation of the condenser resistance from that of the remainder of the circuit involves the use of inordinately high values of total resistance. This necessitates the use of considerable power and close coupling; consequently there is an appreciable percentage of error, the absolute value of which might easily be greater than the resistance of the condenser.

[1] C. D. Callis, Phil. Mag. (7) **1**, 428–432 (1926).

In the description of one method[2] of ascertaining the condenser resistance, the calculated value of the resistance of the circuit exclusive of the condenser is subtracted from the total resistance. But this procedure can not be justified because of the lack of experimental verification of these formulas when large wire and very high frequencies are used.

The differential calorimeter has been used by R. R. Ramsey[3] in determining the resistance of a "low-loss" condenser at one setting. Although based on a fundamental principle, it is with considerable difficulty that calorimetric measurements can be made to yield results of a high degree of accuracy, even though comparatively elaborate apparatus is used. This is well illustrated by the fact that, in the article referred to, the value of the condenser resistance given is the average of values ranging from 0.05 to 0.15 ohms.

In the measurements subsequently described, the condenser resistance constituted at least half the total resistance of a tuned circuit consisting of nothing but the condenser and one circular turn of very large copper wire. A sensitive vacuum tube voltmeter[4] was used to measure the voltage across the condenser at resonance.

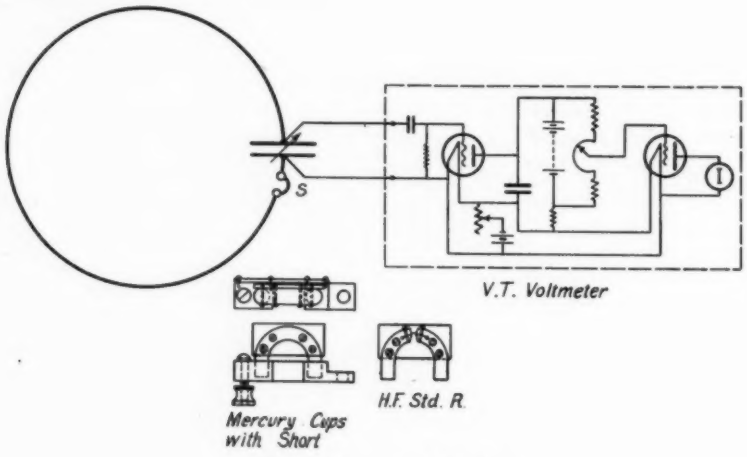


Fig. 1. Diagram of circuit.

The circuit used in these measurements is shown in Fig. 1. The condenser whose resistance was measured was a Bureau of Standards Type .0035μf variable air condenser fitted with a micrometer adjustment. The inductance consisted of one circular turn of B & S No. 0000 annealed bare copper wire. One end of the coil was connected directly to one terminal of the condenser while the other end was connected to the opposite condenser terminal through a short circuit S dipping into mercury cups. The short circuit was made of about 10 cm of No. 0000 copper wire bent so as to fit into the mercury cups. The standard resistances were exact duplicates of the short S except

[2] Weyl and Harris, Proceedings of the Institute of Radio Engineers **13**, 109–121 (1925).
[3] R. R. Ramsey, Phil. Mag. (7) **2**, 1213–1218 (1926).
[4] M. Y. Colby, Journal of Sci. Instruments **3**, 342 (1926).

that about two or three millimeters of the large copper wire was cut out and replaced by an equal length of manganin wire of small enough cross section to make the skin effect negligible at even higher frequencies than any here employed. The mercury cups were held together by a strip of bakelite. The construction of the mercury cups and the standard resistance is shown in detail in Fig. 1. The construction was such that the short circuit could be quickly replaced by a standard resistance without varying the contact resistance and without altering the size, position or configuration of the circuit in the least. The vacuum tube voltmeter was calibrated with 60 cycle a.c. using a noninductive slide wire resistance. The constant voltage a.c. supply necessary for this calibration was obtained by operating a motor generator set from storage batteries.

The measurements were made in the following manner. The circuit was very loosely coupled to a high frequency oscillator made portable by mounting on a cart. The distance between the oscillator and the circuit was from 10 to 50 feet, depending on the amount of induction required. The coefficient of coupling calculated from observations of the current in the oscillator circuit, current in the tuned circuit, and the constants of the two circuits was of the order of 1×10^{-6}, while the power used by the tuned circuit was from 5×10^{-4} to 5×10^{-5} watts. The condenser was adjusted to the desired setting and the frequency of the oscillator varied until the two circuits were in tune. The circuit was then very accurately tuned to resonance by means of the micrometer adjustment. The resonant voltage E_x indicated by the voltmeter was observed; the short S was then replaced by the standard resistance R_s and the new value E_s of the resonant voltage observed. The total resistance R_x of the circuit is given by the relation

$$R_x=\frac{R_s}{E_x/E_s-1}$$

Similar measurements were made at two other settings of the condenser.

A coil of No. 00 copper wire was then substituted for the coil of 0000 wire, and its length was adjusted until its inductance was exactly equal to that of the first coil. The resistance of the new circuit was measured at the same three settings of the condenser and at the same wave-lengths as in the first case. This series of three measurements was again repeated using a coil of No. 2 wire. Thus at each of the three settings of the condenser, three values of the condenser resistance plus the coil resistance were obtained, the coil resistance being different in each case.

If the three loops of different size wire were of the same length, these three values of total circuit resistance R_x plotted against the reciprocals of the diameters D of the corresponding wires would be expected, from theoretical considerations, to give a straight line cutting the resistance axis at the resistance of the condenser R_c. But since the small wire has more inductance per unit length than the large, the three loops of equal inductance vary slightly in length, the loops of smaller wire, of course, being shorter. Therefore R_x would not be expected to be a straight line function of $1/D$ and equal to R_c when $1/D$ equals zero. However, if the clearly justifiable assumption

is made, that the loop resistance is directly proportional to the length l of the wire, the values obtained for R_x would be expected to lie on the straight line,

$$R_x = R_c + Kl/D$$

Accordingly, in each case, the three values of R_x corresponding to a particular wave-length and condenser setting were plotted against l/D and the resulting curve is a straight line. One of these curves is shown in Fig. 2, the intercept being the condenser resistance corresponding to the wave-length and condenser setting indicated.

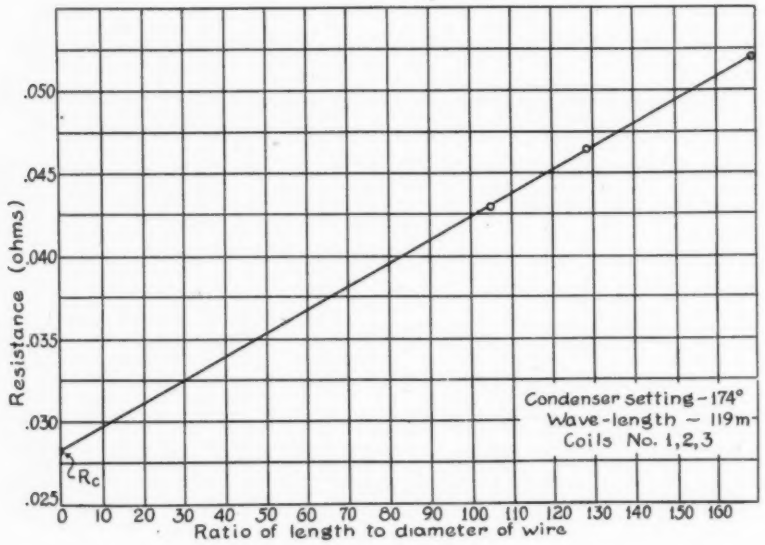


Fig. 2. Graph showing method of separating condenser resistance from coil resistance.

Using another set of larger coils, the values of the resistance of the condenser at the same three settings, but at longer wave-lengths, were determined. Table I shows the six values of condenser resistance R_c obtained by this method. In every case two resistance standards were used, one having a higher resistance and the other a lower resistance than that of the circuit being measured. These standards were measured on a Kelvin double bridge and were accurate to less than one-tenth of one percent at the frequencies used. Standards made of No. 36 and No. 42 manganin wire were checked against one another and were found to agree at all frequencies used. From ten to thirty observations were made in each measurement, the maximum variation usually being less than two percent, and the mean of these values was then taken as the total resistance of the circuit.

As a further check on the validity of the results given here, very careful measurements of the diameters of the wires were made and their high frequency resistance calculated. The agreement between the observed and the calculated[5] values shown in Table I is as close as could be expected in

[5] Bureau of Standards, Circular No. 74.

TABLE I

Values of condenser resistance, R_c, and of the resistance of coils whose specifications are given in Table II.

Condenser setting	Capacity in $\mu\mu f$	λ	Coil	R_x	R_c	R of coil	R of coil calculated
20	483	43.4 m	1	.136 ohm		.023 ohm	.024 ohm
20	483	43.4	2	.144		.031	.030
20	483	43.4	3	.152	.113 ohm	.039	.038
80	1797	83.0	1	.0593		.0173	.0172
80	1797	83.0	2	.0623		.0203	.0212
80	1797	83.0	3	.0696	.0420	.0276	.0276
174	3840	119	1	.0431		.0148	.0147
174	3840	119	2	.0466		.0183	.0180
174	3840	119	3	.0517	.0283	.0234	.0236
20	483	63.0	4	.190		.040	.039
20	483	63.0	6	.208		.058	.061
20	483	63.0	7	.258	.150	.108	.112
80	1797	119	4	.0764		.0272	.0274
80	1797	119	5	.0825		.0333	.0332
80	1797	119	6	.0936	.0492	.0444	.0445
174	3840	172	4	.0542		.0237	.0231
174	3840	172	5	.0579		.0274	.0278
174	3840	172	6	.0676	.0305	.0371	.0372

TABLE II

Coil specifications.

Coil	Wire Size	Diameter	Length
1	0000	1.172 cm	123 cm
2	00	.904	116
3	2	.645	109
4	0000	1.167	238
5	00	.920	227
6	2	.649	214
7	8	.320	194

view of the fact that the wire resistance was usually only a small part of the total resistance measured.

It was found necessary to keep the room in which the measurements were made at a constant temperature, since the variation of the resistance of the circuit with temperature was appreciable.

A more exhaustive investigation of the variation of the resistance of condensers with setting and frequency, as well as with temperature, is now in progress, and the authors expect to be able in the near future to present, in more detail, data concerning these three phases of condenser resistance.

HIGH FREQUENCY LABORATORY,
DEPARTMENT OF PHYSICS,
UNIVERSITY OF TEXAS.
March 17, 1927.

NOTE ON THE PLANE WAVE IN A GAS

By Satyendra Ray

Abstract

Effect of amplitude on velocity of a plane wave in a gas.—In a former paper (Phys. Rev. **28**, 229, 1926) it was pointed out that the velocity of a transverse wave along a string is not independent of the amplitude and that for different frequencies to travel with the same velocity the ratio a/λ must be constant, as for light waves (Zeits. f. Physik **8**, 112, 1921). The same result is here proved for plane longitudinal waves in air.

As an exact equation governing wave motion in air for a plane wave with finite amplitude Lord Rayleigh gives the relation

$$\left(\frac{dy}{dx}\right)^{\gamma+1}\frac{d^2y}{dt^2}=\frac{\gamma P_0}{\rho_0}\frac{d^2y}{dx^2}, \tag{1}$$

where x denotes the equilibrium abscissa and y the actual abscissa in the wave. We note in passing that when the wave is very flat, y is very nearly identical with x and the coefficient (dy/dx) on the left hand side becomes equal to unity. The equation therefore reduces to the form

$$\frac{d^2y}{dt^2}=\frac{\gamma P_0}{\rho_0}\frac{d^2y}{dx^2} \tag{2}$$

of which the solution is

$$y=F(x+vt)+\phi(x-vt). \tag{3}$$

We seek to investigate the displacement wave by putting

$$y=x+\xi, \tag{4}$$

so that Lord Rayleigh's equation becomes

$$\left(1+\frac{d\xi}{dx}\right)^{\gamma+1}\frac{d^2\xi}{dt^2}=\frac{\gamma P_0}{\rho_0}\frac{d^2\xi}{dx^2}. \tag{5}$$

The condition of "flatness" makes $d\xi/dx$ approximately zero so the Eq. (5) reduces to the form

$$d^2\xi/dt^2=v^2d^2\xi/dx^2, \tag{6}$$

where $v=(\gamma P_0/\rho_0)^{1/2}$. In the most general case, however,

$$d^2\xi/dt^2=(v')^2d^2\xi/dx^2, \tag{7}$$

where
$$v' = v(1+d\xi/dx)^{-(\gamma+1)/2}$$
$$= v[1+Ad\xi/dx+B(d\xi/dx)^2+\cdots] \tag{8}$$

and where A, B, etc., are constants.

If ξ be given by the equation

$$\xi = a \sin 2\pi x/\lambda,$$
$$d\xi/dx = 2\pi(a/\lambda) \cos 2\pi x/\lambda,$$

so that the expression for the average value of $d\xi/dx$, $(d\xi/dx)^2$, etc., are functions of a/λ and so is therefore the value of v, which we can determine to as many powers of a/λ as we like.

We content ourselves here with only noting the result that, in common with the results obtained with light vibrations, the velocity of propagation of plane sound waves in air is the same only for geometrically similar waves, the value of the velocity being given in a functional form by the expression

$$v' = vf(a/\lambda). \tag{9}$$

UNIVERSITY OF LUCKNOW,
January 12, 1927.

BOOK REVIEWS

Properties and Testing of Magnetic Materials. THOMAS SPOONER.—This monograph makes available in one place a mass of information hitherto so scattered in engineering publications as largely to miss the attention of physicists. Only ferromagnetic materials are dealt with, and among these the emphasis is upon the commercial materials of widest use, the data concerning electrical (silicon steel) sheet being especially complete.

Part I (187 pages) deals with measurable magnetic properties and with their relations to each other and to the history or momentary state of the material. Fundamental theory is deliberately omitted and the critical reader will find a looseness in the use of units which is probably unavoidable in a work which reports so exactly the present official language of electrical engineering. For example, the following appears on page 9: "The ferric induction is equal to $B-H$, where B is expressed in gausses and H in gilberts per centimeter." In all that relates to high and medium magnetizations under d.c. excitation and under a.c. excitations whether of one or two frequencies, the author may be followed with confidence. His treatment of very low magnetizations is less complete, e.g., there is no mention of Rayleigh's formula for hysteresis at such low inductions that μ is expressible as a linear function of H, and the interesting changes of reversible permeability with changes in superposed d.c. are not discussed although the hysteresis losses for wider displaced a.c. loops are fully treated.

The experimenter will find in Part II (146 pages) a more complete and discriminating account of ferromagnetic test methods than is elsewhere to be found. Though engineering requirements are kept in mind the author has not hesitated to describe research apparatus when any advantage in accuracy or scope can be attained by its use.

Part III (36 pages) deals in general terms with some engineering applications and with magnetic analysis. It is almost independent of Parts I and II, the independence extending even to the repetition of arguments already presented and the duplication of one cut.

The paper, printing, binding and indexing are good. The cuts suffer in many cases from over-reduction. References to periodical literature are not all in the same form and Roman numerals, now generally abandoned, frequently appear. A few errors should be noted. On page xiv μ is omitted from the numerator of the fraction defining permeance and from the denominator of that defining reluctance. On page 6, equation (14), if E is E_{rms}, B should be B_m. On page 45 the resistivity of Co should be near 10, not 100. On page 51, line 4, the statement should be that the effect of magnetization is to increase electrical resistance. On page 208, line 1, read "a small fraction of" for "several times." On page 303, in equation (88), a factor 4 has been omitted from the denominator of the right-hand side. Pp. xiv+385, 6×9, 223 figs., McGraw-Hill, New York, 1927. Price $5.00.

L. W. MCKEEHAN

Sternhaufen. P. TEN BRUGGENCATE. (Siebenter Band, Naturwissenschaftliche Monographien und Lehrbücher.)—This small book on star clusters is of value in bringing together into available form his elaborate unpublished doctoral thesis and several subsequent contributions to scientific journals. Since the subject of globular clusters was rapidly developed a decade ago by the large telescopes, the thesis by ten Bruggencate is the most extensive critical survey of the field.

The distances of the globular clusters and the methods developed in determining these distances have played significant rôles in all recent measures and estimates of the dimensions of the Galaxy and of the remoteness of the extra-galactic stellar systems. It is well known that Bohlin, Shapley, Charlier, Schouten, Curtiss, Kapteyn, and others have been far from accord concerning the value of the methods employed and the value found for the distances. Ten Bruggencate's methodical survey of methods has shown clearly the weaknesses of the deductions by Kapteyn, Schouten, Charlier, and those who found the clusters near at hand and

populated with dwarfish stars; and he agrees in the main with the results obtained at Mount Wilson, which show the enormous remoteness of most of the clusters.

He discusses also the distribution laws for stars in globular clusters and correctly intimates that the vast amount of theoretical study in this field is of very little value. It is an illusion to compare such star systems with gases in equilibrium, and especially to deduce distributional laws from a hopelessly prejudiced sampling of the data.

The monograph also takes up the star counts by Pease and Shapley, the forms of globular clusters, the forms of open clusters, and especially the data on the colors and apparent magnitudes. Too much weight is given, in the reviewer's opinion, to irregularities in the Farbenhelligkeitsdiagramm. The observational data seem to be overworked (again in the opinion of the reviewer who made practically all of the observations and feels their uncertainties); but ten Bruggencate, through a possible overemphasis, is directing attention to an important future need in observational work. Moreover, he is fairly cautious in places where the temptation to speculate on the cosmogonic setting of the clusters must be almost irresistible. Pp. iv+158, 36 figs., 4 plates. Julius Springer, Berlin, 1927. Price 15.00 R.M. unbound, 16.50 R.M. bound.

HARLOW SHAPLEY

Astronomy. *A Revision of Young's Manual of Astronomy.* HENRY NORRIS RUSSELL, RAYMOND SMITH DUGAN, JOHN QUINCY STEWART.—A generation ago the text-books of the late Charles A. Young were the standard for colleges and secondary schools, and his *General Astronomy* was used throughout the land. This was followed in 1902 by the *Manual of Astronomy* of intermediate grade adapted to students without mathematical training. It has been well known for ten years that Russell was working on a revision of Young's Manual, and this has at last appeared under the authorship of Russell, Dugan, and Stewart. The division of the labor is not indicated in the text, but the production of such a work is a three-man job in any case.

The two volumes might be characterized respectively as covering the old and the new in astronomy. Volume I, *The Solar System*, follows Young's text pretty closely, though everything has been checked and revised, and many new illustrations have been provided. The pedagogical value of the work is greatly enhanced by a list of valuable exercises at the end of each chapter.

It is in Volume II, *Astrophysics and Stellar Astronomy*, that the modern progress of the science is demonstrated. The original chapters on the stars which covered one hundred pages have been expanded several fold and entirely re-written. In this volume are also included chapters on the analysis of light, the solar spectrum, atomic theory, and the origin of spectra. This second volume makes a most convenient text for those astronomers whose knowledge of physics antedates some of the revolutionary changes in that science. It has been said that the most striking exemplifications of modern physics are to be found among the stars, e.g., the tests of the theory of relativity, the annihilation of matter, the density of the companion of Sirius, and so on, and students will find such things here in their astronomical setting. The chapter on the constitution and evolution of the stars gives results of the latest theories by such workers as Russell, Eddington, and Jeans, and will probably impress the general reader that there is much more to astronomy than the dull routine of exact measurement.

The exposition is simple and clear, and the work may be heartily recommended to the intelligent layman. The reviewer does not admire the excessive use of parentheses (characteristic of the style of the senior author), for most mortals cannot operate two trains of thought simultaneously, but not every mind from Princeton can be limited to a single track.

The mechanical production of the books is first-class, the division into two volumes of convenient size facilitating the work of teachers who desire to provide separate semester courses. The moderately thin paper enables a great amount of material to be put in a small compass, and the reproductions of modern astronomical photographs are good but do not represent the last word in pictorial effect. However, there is no need to search for minor blemishes in this monumental work; it will remain as the standard text and reference book for the serious student for a long time to come.

Volume I, xi+470+xxi pp., 190 figs.; Volume II, xi+462+xxx pp., 127 figs., Ginn & Co., 1927. Price $2.48 per volume.

JOEL STEBBINS

Lehrbuch der Electrodynamik. Band 1. J. FRENKEL.—This excellent text consists of four sections: an introduction on vector and tensor analysis; electromagnetic effects independent of the time; electromagnetic effects dependent on the time; the relativity theory. In his vector notation the author has departed from the awkward continental use of parentheses for scalar product and brackets for vector product, and has adopted a notation very nearly the same as that advocated by Gibbs. In fact the chief divergence from Gibbs' notation is in the omission of the dot between the vectors forming a scalar product. The cross is used to designate vector product, unit vectors are employed, and ∇F and $\nabla \times F$ are used as alternatives to div F and rot F respectively. The gradient, divergence and rotation (curl) are defined by integrals over closed surfaces, a procedure which has the advantage of emphasizing from the start the invariance of these expressions for rotations of the coordinate axes.

The author introduces the subject of electrostatics from the standpoint of the elementary dipole and adopts the novel procedure of defining the electric intensity as the ratio of the maximum mechanical torque on the dipole to its electric moment. Steady currents are considered early in this section, and the subjects of electrostatics and magnetostatics are discussed in parallel rather than in series. No effort is made to take up in detail the solution of electrostatic problems by the use of spherical harmonics.

Maxwell's equations are developed early in the third section and much of this section is devoted to the electrodynamics of the electron. Among the topics of discussion are retarded potentials, the field of an oscillating dipole, electromagnetic waves, retarded and simultaneous fields of a moving point charge, the electromagnetic theory of mass, electromagnetic energy and radiation, energy of translation and of rotation of the Lorentz electron, the magneton.

The final section contains the usual topics connected with the special relativity theory, including the representation of E and H as components of a six-vector, and the various compact formulations of the more important electromagnetic relations in four dimensional tensor language. The relativity mechanics is also developed for the case of a particle in external electric and magnetic fields, and the Hamilton-Jacobi partial differential equation is set up. Applications are given, such as the revolution of an electron about a positive nucleus as in the Bohr model of the hydrogen atom.

The arrangement of topics is along conventional historical lines in that the subject of electromagnetism is developed fairly completely before the introduction of the relativity principle. In the reviewer's opinion a more logical treatment is assured by inverting the order and basing the whole subject of electrodynamics on the relativity principle as in the emission theory. Pp. x+365. Julius Springer, Berlin, 1926. Price unbound R.M. 28.50, bound, R.M. 29.70.

LEIGH PAGE

Leitfaden der Praktischen Experimentalphysik für Vorlesung und Unterricht. REINHARD MECKE and ANTON LAMBERTZ.—Those who can read German will find this book a helpful guide in setting up lecture demonstrations for classes in first or second year physics. It is, however, as the preface indicates, nothing more nor less than a reprint of a portion of Vol. 1 of Geiger and Scheel's recently published many-volumed "Handbuch der Physik." The book is much smaller and more concise than such works on physical demonstrations as those of Weinhold and of Frick, and contains but little on general lecture-room equipment. On the other hand it offers useful hints on the conduct of lectures, and is rich in diagrams, tables, and numerical data for blackboard presentation. Most of us who have experienced the vicissitudes of lecture-demonstrating will agree with the authors that "an experimental lecture is both a *Kunstwerk* and a *Kunststück*"! Most of the demonstrations are of the familiar and well-established sort. Among the evidences of up-to-dateness may be mentioned the demonstrations of magnetic hysteresis by means of the cathode-ray oscillograph, photo-electricity, the neon tube, the Johnsen-Rahbek effect, three-electrode vacuum tubes, and alpha ray tracks. A few minor errors have been noted; for example, an inconsistency in the list of overtones on page 41, the interchanging of oxygen and nitrogen in Table 24 on page 59, and an erroneous value for the melting point of zinc on page 48. Pp. vi+195. Springer, Berlin, 1926. Price, unbound R.M. 9.60, bound R.M. 10.80.

W. G. CADY

Müller-Pouillets, Lehrbuch der Physik, 11th edition, 3rd vol., 1st half. **Physikalische, chemische, und technische Thermodynamik.** (including Heat Conduction), edited by ARNOLD EUCKEN with the cooperation of U. EBBECKE, M. JAKOB, A. MAGNUS, F. POLLITZER, F. SAUERWALD, R. SUHRMANN, and G. ZERKOWITZ.—The section of this standard work dealing with heat has been entirely rewritten since the tenth edition. The large amount of new material has necessitated dividing it into two volumes; the first volume, which is the one under review, deals with the phenomenological aspects of heat, while a second volume is promised dealing with the various aspects of kinetic theory. It is impossible in a review of this character to do much more than indicate the contents, which are as follows:

Introduction

General Part

- A. Experimental Methods
  - Thermometry
  - Calorimetry
- B. The Fundamental Laws of Thermodynamics
  - The first law
  - The second law
  - Historical survey of the development of the principles of thermodynamics

Special Part

- I. Systems at Uniform Temperature
  - A. Homogeneous one-component systems
    - Characteristic equation
    - Thermal equation of state
  - B. Heterogeneous one-component systems
    - Equilibrium between different states of aggregation
    - Energy changes accompanying phase changes
    - Surface phenomena
    - Velocity phenomena during change of phase
  - C. Homogeneous systems of more than one component
    - General properties of mixtures and solutions
    - Equilibrium in gaseous mixtures and solutions
    - Transient phenomena accompanying the establishment of equilibrium
  - D. Heterogeneous systems of more than one component
    - The equilibrium of heterogeneous systems from the phenomenological point of view
    - Thermodynamic treatment of special systems of more than one component
    - Boundary surface phenomena
    - Transformation and reaction velocity
- II. Systems not at uniform temperature
  - A. Thermal processes neglecting the effects of work
    - Equilibrium and chemical reaction velocity
    - Heat conduction
  - B. Technical processes with generation of work
    - General thermodynamic fundamentals of thermodynamic engines
    - Thermodynamic engines with external combustion
    - Thermodynamic engines with internal combustion
  - C. Technical processes with absorption of work
    - Compression of gases
    - Transport of heat with expenditure of work (Refrigerating machines and thermal pumps)
    - Separation of gaseous mixtures

Appendix

Physiology of heat

In general the work seems to have been brought thoroughly up to date, and will prove to be a most valuable reference book, many parts of which can be used, as suggested by the title, for the instruction of advanced students. The major part of the book was written by A. Eucken, which of itself is sufficient guarantee of its authoritative character. It is perhaps surprising that in a book of this scope no mention is made of the thermodynamic properties of crystals, which can best be treated, as was done by Voight, by methods entirely thermodynamic in spirit.

The disconcerting aspect of all this recent German activity in producing indispensable reference books is that it does not appear where the average library is to get the money to buy them all, nor does it appear how the publishers can escape financial loss. Pp. xviii+1185, 575 figs. Friedr. Vieweg und Sohn, Braunschweig, 1926.

P. W. BRIDGMAN

The Enlarged Heat Drop Tables. HERBERT MOSS.—For the British Engineer Callendar's steam tables (E. Arnold and Co., London, 1924) are standard. The tendency everywhere in steam engineering is to push up the boiler pressure so that the current tables are becoming inadequate for considerable pioneering work. The available experimental data for these higher pressures are increasingly scanty and uncertain, particularly above 300°C. Hence, Moss has taken Callendar's systems of equations which agree satisfactorily over the known experimental region and has used them to cover the range from 400 to 2000 lbs/sq. in. Ultimately, any extrapolation must be checked by experimental work. This is a tedious and difficult job, so that perhaps such extrapolated data are the best temporary expedient. These "adiabatic heat drop" tables give the heat per lb. of steam convertible into mechanical work by an ideal Rankine cycle working between the specified limits; the Rankine cycle being accepted in British practice as the most satisfactory ideal approximation to an actual engine. Such an energy quantity is dependent on both pressure limits and on the temperature rise above saturation, being particularly sensitive to the low pressure. To cover both limits the heat quantity is given in successive tables, each for a particular low pressure, where each table lists this heat for saturation pressures from 400 to 2000 lb/sq. in. and also for temperature rise above saturation up to 300°F (superheats). This requires rather large steps in the tabulation, but it is claimed interpolation may be made with about the accuracy (in the sense of consistency) of the tables. In this connection, reference might be made to the work being done by the Am. Soc. of Mech. Eng. through their committee on "Steam Research," progress reports of which are published yearly in "Mechanical Engineering." There is a very definite need for further data on the properties of water, say above 300°C. Pp. 88, Edward Arnold, London, and Longmans Green, New York, 1925. Price $3.75.

J. R. ROEBUCK

Enlarged Mollier Diagram for Saturated and Superheated Steam. H. L. CALLENDAR.—This table puts in graphical form the results of Callendar's work on steam. The chart is 66×80 cm and covers the pressure range of 0.2 to 2000 lbs per sq. in. and the temperature range of 100 to 700°F. Along with the equations and tables it forms the basis for Moss's heat drop tables. Curves also give the volume superheat, pressure, and temperature relations. To help in using the very complicated figure, part of the lines and symbols are printed in red. It is a well-printed diagram on good paper. Edward Arnold and Co., London, for the British Electrical and Allied Industries Association, 1926, and Longmans Green and Co., New York. Price $1.35.

J. R. ROEBUCK

Fogs and Clouds. W. J. HUMPHREYS.—This is an entertaining little book which can be counted upon to provide a few hours of pleasant and instructive reading, with the privilege of looking at some remarkable photographs. Physicists, *qua* physicists, will probably be interested most by the chapters entitled *Evaporation and Precipitation*, *Fogs*, and *Cloud Miscellany*. In these, Mr. Humphreys has given, among many other bits of diverse information,

a description of the processes of formation and dissolution of clouds; a catalogue of the sorts of condensation-nuclei that occur in the air, and notions about the number of these and the sizes of the droplets of fog or rain which form around them; many interesting facts about the sizes and localities and velocities of clouds; a theory of the genesis of rain; and commemorations of some of the pioneers in the study of clouds. In the closing chapter, *Cloud Splendors*, the author gives a theory of lightning, and much information about the haloes, coronae, parhelia and other luminous phenomena due to water-droplets or ice-crystals in the sky. Physicists will wish that the arguments for the theories and the ways in which some of the data were obtained had been given in greater detail; but Mr. Humphreys would probably retort that he has satisfied that desire in other books, and designed this as a popular presentation. The central and longest chapter, *Cloud Forms*, contains an official list of definitions of the various types of cloud, expanded by further descriptions and illustrated by multitudes of pictures. I fear that even after repeated re-reading of this chapter, one would hardly be able to look up at the sky and instantly classify whatever sort of cloud he might see there floating—that is probably an art to be learned only by first-hand experience and demonstration in the field; but, as one who hitherto has known by name no form of cloud except the cumulus and the nimbus, I hope to be able to recognize at least the cirrus and the stratus henceforward. It is interesting to read of clouds which remain stationary while the wind and the water drift through them, condensing on the windward and evaporating on the leeward side. Not many scientific books are written in so vivacious, witty and lucid a style, although even this one is marred by some long sentences not written carefully enough to be clear, by a trace of turgidity in some of the poetic passages, and by the use of *wonder* and *master* as adjectives. The illustrations, as I have intimated, are numerous and many among them are superb; one would give much to witness some of the phenomena which Mr. Humphreys or his friends have caught with their cameras, and would pray to be spared from seeing some of the others. Pp. xvii+104, 93 figs.; Williams & Wilkins Company, Baltimore, 1926. Price $4.00.

KARL K. DARROW

Stereoscopic Drawings of Crystal Structures. Edited by M. VON LAUE AND R. VON MISES.—It is well known that spacial models are indispensable for the study of crystal structure. This collection of stereoscopic pictures has been prepared to supply that need without the cost and the large amount of space needed for the usual wire models. There are twenty-four stereoscopic drawings accompanied by a booklet containing an explanation of each in English and in German. The drawings have been selected to show the fourteen Bravais lattices and eight different crystal structures of the simpler sort. These are rocksalt, caesium chloride, zincblende, diamond, white tin, wurtzite, fluorspar, cuprite, and cadmium iodide. The names and interatomic distances of other crystals belonging to these eight types are also given. These drawings cannot be said to entirely replace good spacial models which can be examined at will from any desired orientation, but their convenience and low cost makes them very useful accessories in the study of crystal structure.—43 pp., 3 figs. +24 plates. Julius Springer, Berlin 1926. Price 15 M.

JOSEPH VALASEK

Handbuch der Physikalischen Optik. Edited by E. GEHRCKE. Vol. I. First Half.—Following the recent rapid advances in physical optics it has become desirable to have an up to date summary of the present status of the subject. This set of books is therefore very welcome at this time. In general, the authors have adhered to the original intention of confining the first volume to classical or wave optics and the second to modern or quantum optics. Thus the first volume begins with several chapters on photometry including spectrophotometry, colorimetry, and recording photometry. This is followed by a chapter on the velocity of light and several chapters on refraction, the first of which deals with the instruments and methods used in its measurement. An excellent discussion is given of refraction and dispersion in general, and this is followed by a chapter on the relations of refraction to chemical composition and physical state. However, the physical bases for the various refraction and dispersion theories are reserved for another part of the book. Here one finds only the discussion of the formulas in the light of experimental results. There is considerable space devoted to re-

fraction by media with continually varying indices and to astronomical and terrestrial refraction. The last chapter is on interference and its many applications in experimental optics. There are many references throughout the book, making it easy to get further information on any of the subjects when desired. Pp. 470+VIII, 233 figs. Verlag von Johann Ambrosius Barth, Leipzig 1926. Price 40 R.M. JOSEPH VALASEK

Handbuch der Physikalischen Optik. Edited by E. GEHRKE, Vol. II. First Half.—The first half of volume one has been reviewed above. Volume two begins with photochemical laws and reactions. This is naturally followed by a chapter on photography which deals with both the chemical and physical sides of the subject. In view of recent interest in photographic photometry, an important section is that on sensitometry and the theory of the photographic plate. Applications of photography to technical reproduction are also given, and so are the various methods of color photography. The remainder of the book is concerned with some of the problems of spectroscopy. This subject is here taken up from the empirical point of view with the emphasis largely on apparatus, technique, and discussions of results, rather than on the mathematical development of the theory. The subject matter includes spectral analysis in general, fine structure of spectral lines, photo- and chemi-luminescence spectra, radiation potentials, and series laws in line spectra. The various chapters are written by well known authorities in their respective fields. Numerous references facilitate the looking up of further information. In all, this is an excellent work for which there has been a great need in view of the growing importance of physical optics as the center of interest in physics of today. Pp. 418+V, 166 figs. Verlag von Johann Ambrosius Barth, Leipzig 1927. Price 37.50 R.M. unbound. JOSEPH VALASEK

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY

MINUTES OF THE WASHINGTON MEETING, APRIL 22–23, 1927

The 145th regular meeting of the American Physical Society was held at the National Academy of Sciences in Washington, D. C. on Friday and Saturday, April 22 and 23, 1927. The presiding officers were Professor Karl T. Compton, President of the Society, and Professor Henry G. Gale, Vice-president of the Society.

On Friday evening there was a dinner for the members of the Society and their friends at the Hotel Raleigh. The speakers at this dinner were Professor R. A. Millikan, Dr. E. E. Slosson, and Professor P. M. Debye.

At the regular meeting of the Council held on Friday, April 22, 1927, three were transferred from membership to fellowship and nineteen were elected to membership. *Transferred from Membership to Fellowship*: F. S. Brackett, J. J. Hopfield, and R. de L. Kronig. *Elected to Membership*: Charles S. Allen, Howard H. Brinton, C. J. Campbell, C. C. Cole, W. E. Curtis, Ralph K. Day, Milan W. Garrett, Newell S. Gingrich, Philip C. Jones, S. C. Lind, Noel C. Little, H. E. Marsh, Wm. Crawford McKissack, Jr., J. Howard McMillen, John G. Moorhead, Charles A. Rinde, Harry Rolnick, Henry Semat, and Lloyd P. Smith.

The regular program of the American Physical Society consisted of 94 papers, numbers 12, 14, 21, 35, 37, 43, 44, 46, 61, 72, 87, 88, 91, 92, 93, and 94 being read by title. The abstracts of these papers are given in the following pages. An **Author Index** will be found at the end.

HAROLD W. WEBB, *Secretary*

ABSTRACTS

1. A thermo-magnetic effect on gases. NOEL C. LITTLE, Bowdoin College.—If a temperature gradient is maintained in a gas completely enclosed by a metal box placed between the poles of an electro-magnet, the isothermal surfaces in the gas are warped upon the excitation of the field, provided the field is non-uniform. That the effect varies with the nature of the gas was shown by a thermo-couple placed midway between the ends of the pole pieces where the temperature gradient was 15 degrees per centimeter. When a field of 15 kilograms was excited, drops in temperature were observed as follows: in air 16 degrees, in oxygen 18 degrees, in nitrogen and carbon dioxide none, in hydrogen 6.6 degrees, in propane 16 degrees.

2. Critical potentials of copper. RICHARD HAMER and SURAIN SINGH, University of Pittsburgh.—Critical potentials of copper have been investigated in the region up to 30 volts. The method adopted was to search for repeatedly occurring breaks in the current potential curves when a copper cylinder and insulated central copper rod suspended in a highly evacuated quartz tube were heated to about 700°C. The measurement of the potentials was made to depend on the determination by a potentiometer of the e.m.f. across a standard resistance

in the same portion of the series of standard resistances as that across which the applied potentials were taken. This permits the measurement of critical potentials to be made as accurately as desired. The breaks or changes of slope were taken to indicate the critical potentials and were checked by plotting the differential curves from the observed deflections for the applied equal changes in potential. The preliminary results for copper are as follows: 3.3, 7.9, 14.2, 19.5 and 25.3 volts for the range mentioned.

3. The significance of photo-electric conduction in crystals. A. M. MACMAHON, University of Chicago.—The numerous successes of the Rutherford-Bohr atom model suggest interesting possibilities which the conception may have when applied, with appropriate modifications, to the phenomena of the solid state—e. g., the conduction of electricity. An explanation of the light-sensitiveness of certain crystalline substances, particularly selenium, follows at once. Simultaneous differential equations, whose solution leads to an expression of the same form as the empirically determined one (Phys. Rev. **29,** 219 (1927)) relating the change in current through a specimen to the time of illumination, are readily obtained upon the assumption of a shift to either of two distinct configurations of the outer electrons when light is absorbed. The picture seems more plausible than those of molecular changes, proposed by previous investigators to account for the exposure and recovery characteristics of selenium, and is in agreement with x-ray analyses which show that the crystal lattice is not perceptibly disturbed even under strong illumination. An explanation of the effect of previous illumination is afforded, and the transmitted action discovered by Brown and Sieg (Phil. Mag. **28,** 497 (1914)) interpreted. This view of the conduction of electricity gives physical meaning to electrical resistance in agreement with the approach to perfect conductivity found for the metals at very low temperatures.

4. Relation between light intensity and photo-current in selenium. R. J. PIERSOL, Westinghouse Research Laboratory, East Pittsburgh.—This is a continuation of work previously reported (Phys. Rev. **29,** 362 (1927)) in which the variation of photo-sensitivity with temperature pointed to the theory that selenium conductivity is photo-electric. Present work on white light and ten spectral frequencies shows a linear relation within experimental error between the light intensity and the square of the photo-current. This data is shown in the form of curves for the various colors of light. The results are further substantiation of the photo-electric theory of selenium conductivity.

5. Photo-electric threshold of bismuth crystals. T. J. PARMLEY, Cornell University.—Single bismuth crystals were grown according to Bridgman's method. The apparatus was mounted in a bell jar and evacuated to a pressure of 10^{-6} mm. Then a razor blade as the effective edge was used to open the crystal along a plane and the specimen was moved into position in a Faraday cylinder where readings were taken, the mechanical operations being controlled by external electromagnets. The light source included a quartz mercury vapor lamp and quartz monochromator. Saturation currents were measured by means of a Dolezalek electrometer of 1500 mm per volt sensitivity connected directly to the crystal. The photo-electric threshold of a freshly prepared surface was found to lie between 2804 and 2894 A. Fatigue curves extending over approximately an hour's time were obtained.

6. Effect of oxygen on photo-electric emission from potassium. L. R. KOLLER, General Electric Co.—Some measurements were made to determine the effect of adsorbed oxygen on the photo-sensitivity of a potassium photo-electric cell. Sufficient oxygen was admitted to form an adsorbed layer one atom deep. This cleaned up almost at once and no change in sensitivity was observed. Oxygen was then admitted in doses of about 100 microns. There was no appreciable change in photo-sensitivity until after 355 microns had been adsorbed. The next 800 microns resulted in a three-fold increase in sensitivity. After this, each dose resulted in an immediate drop in sensitivity followed by a gradual recovery, but for each successive dose, the drop was to a new low level and the recovery less complete. The explanation of these phenomena lies in the absorption of oxygen by the potassium. Small quantities

diffuse in so that no oxide is left on the surface. After the potassium is nearly saturated, the diffusion in is slowed down so that the effect on the surface can be observed. The gradual recovery takes place as the oxide diffuses in and a fresh potassium surface is formed. Eventually the potassium is all converted to oxide and the sensitivity is completely destroyed.

7. Electron emission and diffusion constants for tungsten filaments containing various oxides. S. DUSHMAN, D. DENNISON and N. B. REYNOLDS, General Electric Company.—In general the emission phenomena observed for these filaments are similar to those observed by I. Langmuir with tungsten containing thoria. Reduction of the oxide occurs at a very high temperature and activation at a lower temperature. None of the monatomic films produced in this manner are as stable as those obtained with thoria, owing both to more rapid diffusion and evaporation. This makes it difficult to obtain accurate emission data for completely covered films. Using the equation $I=AT^2\epsilon^{-b/T}$, the values of A and b obtained for different films are as follows:

Metal	Yt	La	Ce	Zr	U	TH
A	7.0	8.0	8.0	5.0	3.2	3.0
B	31,300	31,500	31,500	36,500	33,000	30,500

Measurements have also been made on diffusion constants (d) and rates of evaporation (E) for these films. The following table gives a summary of results obtained for 4 mil filaments at T = 2000. The values for Th are taken from Langmuir's paper.

Atom	$d\times10^{11}$(cm² sec.$^{-1}$)	Heat of Diffusion	$E\times10^{9}$(atoms/cm²sec.)	Atomic Weight
U	1.3	100,000	>Th	238.5
Th	5.9	94,000	1.53	232
Ce	95.	83,000	1450	140.3
Zr	324	78,000	68	91.
Yt	1820	62,000		89.

8. Theory of the shot effect. HAROLD A. WHEELER, Johns Hopkins University.—The shot effect, described by Schottky, is the phenomenon of current fluctuations in a stream of electrons limited by random emission, as from a hot filament. Previous derivations of the magnitude of the shot effect have been based on equations derived in the abstract by the theory of probability. In the present paper, a simple derivation of the equation, $(I_0^2)_{mean}=eI_a/2RC$ (I_a=average space current), is given in terms of the familiar discharge current in a simple series circuit (R, C, L). This is followed by a Fourier integral derivation of the continuous frequency spectrum of the current fluctuations: $d(I^2)_m/d\omega=eI_a/\pi$. The simple derivation is thereby linked with former work and the correctness of the assumptions verified.

9. A study of the lag of the Kerr effect for several liquids as a function of the wave-length of the light. J. W. BEAMS, National Research Fellow, and Ernest O. Lawrence, National Research Fellow, Yale University.—We have shown that an upper limit to a possible lag of the Kerr effect in carbon bisulphide is 3×10^{-9}sec. However, measurable lags have recently been observed for various liquids (method described in J. O. S. A. & R. S. I., **13**, 597(1926); also paper by Beams and Allison in press). The differences between the lags of the Kerr effect for several liquids have now been investigated as a function of the wave-length of the light. The results indicate that the lag differences are independent of the light wave-length. The following are the excess lags over a possible lag in carbon bisulphide: Bromoform 3.3 10^{-9}sec: Chloroform 3.8 10^{-9}sec: Ether 6.0 10^{-9}sec.

10. The instantaneity of the photo-electric effect. ERNEST O. LAWRENCE, National Research Fellow, and J. W. Beams, National Research Fellow, Yale University.—The grid and potassium coated plate of a three electrode photo-electric cell were attached in series with a bias battery accross one of two condensers which in turn were connected in parallel with a spark gap. The arrangement was such that when the potential across the spark gap was nearly a maximum the field between the photo-cell plate and grid was such as to draw electrons to the grid and on to the collecting electrode. A definite time after the discharge of the spark

(equal to the wire path connecting photo-cell to spark gap divided by the velocity of light) the field reversed, thereby preventing electrons from leaving the plate. By varying the wire path this device permitted a study of the times of ejection of electrons by short flashes of light from the spark, produced by an earlier described method. Our experiments indicate that electrons start coming off a potassium surface the instant light falls on the surface and cease being emitted the moment the illumination is cut off, within a possible experimental error of 3×10^{-9}sec.

11. Polarization of resonance radiation in strong magnetic fields. Breadth of spectral lines. A. ELLETT, University of Iowa.—The polarization of resonance radiation excited by the D lines has been measured for various states of polarization of the exciting light and for magnetic fields up to 3500 gauss. With the electric vector of the exciting light parallel to the magnetic field the polarization reaches a value of 49 ± 1 percent in a field of 500 to 600 gausses and does not change with further increase of the field. With the electric vector perpendicular to the field the polarization reaches a value of $32.8\pm.5$ percent at 500 gauss and remains constant to 1200 to 2000 gauss depending on the breadth of the exciting line. This line breadth may be made so small that first one and then both of the perpendicular components of D_2 fall outside the exciting line. D_2 excited by the inner perpendicular component alone is completely polarized. From the magnitude of the fields at which these components cease to be excited it is evident that the line breadth is about what one expects from Deppler shift alone, though it may exceed this slightly.

12. The magnetic moment of helium and molecular hydrogen. IRVIN H. SOLT, University of Cincinnati.—A narrow beam of molecules or atoms was produced by means of two slits, $.03\times2.2$ mm, three centimeters apart. The space between the slits was connected to a mercury vapor pump. The beam passed through a non-homogeneous magnetic field produced by a pair of pole pieces, one wedge shaped and the other slotted, after the manner of Stern and Gerlach. The beam was explored by a platinum wire .017 mm in diameter and 2.5 mm long which formed one arm of a Wheatstone bridge. No influence of the magnetic field on the beam was observed for a gradient of about 1.5×10^5 gauss per cm. The experiments are being continued with a view toward increasing the sensitivity of the apparatus so that other gases can be investigated.

13. The magnetic moment of atomic iodine. JOHN B. TAYLOR and T. E. PHIPPS, University of Illinois.—The magnetic properties of atomic iodine have been investigated in an apparatus which is a modification of that used by the authors in the determination of the magnetic moment of the hydrogen atom. The iodine was dissociated in an electrically heated tiny quartz tube furnace and the ray of atoms received on a liquid air cooled glass target, which had been first coated with a thin film of mercury. This was a very sensitive detector. A multiple separation of the ray in a magnetic field, corresponding to a magnetic moment of two, has been predicted spectroscopically for the iodine atom. The rather imperfect images thus far obtained show a distinct deflection of the ray, and apparently such a multiple separation into more than two lines corresponding to a magnetic moment greater than one. This latter point and the relative intensities of the lines cannot yet be decided with certainty.

14. Method of measuring the distribution of magnetic fields. J. TYKOCINSKI-TYKOCINER and J. KUNZ, University of Illinois.—The following method has been developed for the determination of field inhomogeneity between pole pieces as used in the magnetic moment measurements of atomic rays. Two bronze ribbons carrying a mirror and stretched on a frame move between the poles of an electromagnet whose field distribution in the air gap has to be determined. By means of two micrometer screws the frame can be moved either along or across the field. From the deflection of the mirror produced by direct currents passing through one of the wires and then through the other and then through both of them the magnetic field intensity and its gradient can be determined from point to point. Satisfactory results were obtained when currents of equal intensity flow through both wires simultaneously. For a current i_1, flowing through both wires in the same direction the angular deflection is

tan $\alpha_1/2=c(H_2-H_1)i_1/d$ for a current i_2 flowing in opposite direction tan $\alpha_2/2=c(H_2+H_1)i_2/d$ where H_1 and H_2 are the magnetic field intensities, c is a constant and d the distance between the wires. For small angles α the following relations are obtained $H_1=d(a_1/i_1+a_2/i_2)/4cD$ $H_2=d(a_1/i_1-a_2/i_2)/4cD$ and $\partial H/\partial x=(H_2-H_1)/d=a_1/2ci_1D$, where D is the distance between the scale and mirror, and a_1, a_2 are the scale readings corresponding to the angles α_1 and α_2.

15. The origin of the magnetic fields of sun spots. W. F. G. SWANN, Yale University.—Recently the writer has developed a modification of the laws of electrodynamics according to which among other things, a neutral rotating sphere should give rise to a magnetic field which at the pole is proportional to Dv^4 where D is the density and v the peripheral velocity. A sun spot is usually regarded as a U-shaped structure with appreciable rotation confined to a depth of the photosphere comparable with the diameter of the spot. As regards order of magnitude we should thus expect that the magnetic field of a sun spot would be comparable with that of a sphere rotating with the same peripheral velocity. According to this, if subscript s refers to the sun spot and e to the earth $H_s/H_e=(D_sv_s^4)/(D_ev_e^4)$. Taking H_e as 0.5 for the poles, $D_s=5.5$, $v_s=0.5$ kilometer per second, $D_e=4\times10^{-6}$, we find that the value of v_s necessary to account for a value of H_s equal to 2000 gauss is 80 kilometers per second. This value is not unreasonable for a sun spot. On applying the theory to the planet Jupiter we calculate a magnetic field of the order 50,000 gauss for that planet.

16. Magnetic susceptibility of single-crystal metals. C. NUSBAUM, Case School of Applied Science.—The magnetic susceptibility of single-crystals of bismuth and antimony has been measured by a modified form of Terry torsion balance. The single-crystals of these metals are characterized by a three-fold axis of rotational symmetry, with the cleavage planes perpendicular to the principal axis. The crystals are rotated around an axis perpendicular to the principal axis of the crystal. The mass susceptibility (x) for bismuth in a direction parallel to the principal axis is 1.13×10^{-6} and in a perpendicular direction 1.32×10^{-6} dyne-cms. Corresponding values for antimony are 0.497×10^{-6} and 1.38×10^{-6}, respectively.

17. Results of earth-resistivity surveys in connection with the study of earth-currents at Watheroo, Western Australia and Ebro, Spain. W. J. ROONEY and O. H. GISH, Department of Terrestrial Magnetism, Carnegie Institution of Washington.—To supplement the potential registrations and so ascertain the earth-current density, earth-resistivity surveys have been made at the Magnetic Observatory of the Carnegie Institution of Washington, Watheroo, Western Australia, and at Ebro Observatory, Tortosa, Spain. At Watheroo, situated on a sandy plain, the resistivity at the surface varies with position from 90 to more than 4,000,000 ohms per centimeter cube. The mean values for the region are extremely low, the average to depths of 60 to 100 meters being 700. Beyond this depth the values increase slowly, reaching 5,000 for 600-meter depths, the greatest explored. At the Ebro Observatory, located in the valley of the river Ebro the resistivity, although generally low near the surface, is always higher than that at Watheroo when depths beyond 30 meters are included in the measurements. The average value to 100-meter depths is 9,600 and increases to a little over 12,000 for 300 meter depths, the greatest explored there. Records of potential gradient for a number of years give values approximately one magnitude higher at Ebro than at Watheroo. The resistivity results, therefore, indicate that the current density is of about the same magnitude at both places.

18. The Hall effect and resistance of sputtered tellurium films. F. W. WARBURTON, Cornell University.—According to Eldridge and Page the Hall coefficient should be proportional to resistance, but Mackeown's experiments with thin films have shown that the Hall e.m.f. remains constant when the resistance changes by aging. The present experiment was undertaken to find the relation of the Hall coefficient to resistance when the latter is changed by temperature or by means other than aging. Preliminary results show that the Hall e.m.f. in very thin films of tellurium is directly proportional to resistance, both when the temperature coefficient of resistance is positive, as well as when it is negative but is independent of change in resistance due to absorbed gas.

19. Magnetic properties of iron in high frequency alternating current fields. JOHN R. MARTIN, Case School of Applied Science.—A number of investigators have studied the losses due to eddy currents and hysteresis in iron when placed in high frequency alternating current fields, but the results obtained are in wide disagreement. Using a new method, the author has investigated the variation of this loss with the frequency for several areas of cross section. The total loss is considered as the equivalent of an absorbing resistance and by measuring the value of this resistance at resonance, the loss may be determined from the I^2R relation. With magnetizing currents of 3, 4 and 5 ampere-turns per cm, the measurements are made on short iron cylinders of various cross sectional areas, at frequencies ranging from 5.20×10^5 to 9.08×10^5 cycles per second. The loss is found to increase with frequency in the small samples and to decrease with frequency in the larger. At any particular frequency the loss is an inverse function of the area. This is due to the magnetic shielding effect of eddy currents in the large samples and the disagreement between previous investigations may thus be explained.

20. On refraction in moving media. N. GALLI-SHOHAT, University of Michigan.—For light passing from vacuum to a moving medium it is customary to construct a "relative ray" with the help of Fresnel's drag coefficient $(1-1/n^2)$. If one applies Fermat's principle both to this ray and to the wave normal, it may be shown that only one of them obeys Snell's Law. The variation of one path affects the other in such a way that it would be necessary to neglect first order terms in v/c in order to preserve Fresnel's form of the drag coefficient. It is possible however to preserve Snell's law for both rays by a modification of the drag coefficient so that it depends on the angle of incidence and assumes the customary form for normal incidence.

21. The theory of the magnetic nature of gravity and electrons. CORNELIO L. SAGUI, Castelnuovo dei Sabbioni, Italy.—In a preceding paper Balmer's series were derived from equation $(x^2+x)/2=y$ and other possibilities as to their behavior were investigated. The attempt is made to give a physical meaning to those mathematical results by considering the structure of an atom as an assembly of protons and electrons. Electrons are considered as an assembly of a large number of electromagnetic quanta and reasons are given for their negative electric charge. Again, a proton would result from an assembly of electrons and its positive charge is considered as due to a symmetrical difference in its structure, resulting in the opposite to an electron. The Einstein's equation $eV=h\nu$ was considered in the light of the theory and frequencies ν were supposed to be due to the splitting up of the electrons themselves into smaller units of energy. The effect would be wholly a mechanical one. The atomic fluorescent absorption, the Compton effect, the phenomena of absorption of light by atoms and their re-radiation, as well as the Brownian movements are all investigated from the point of view of the electromagnetic quantum theory.

22. Ionization by collisions of the second kind in mixtures of hydrogen and nitrogen with the rare gases, GAYLORD P. HARNWELL, Princeton University.—The behavior of ionized mixtures of hydrogen and of nitrogen with helium, neon, and argon separately have been investigated by means of a positive ray analysis. (See abstract No. 24, New York Meeting, Feb. 26, 1927.) Due to the secondary products of ionization the variation with pressure of the types of ions present was found to be more complicated than in the rare gas mixtures previously studied. However, in all cases so far investigated the results are in agreement with those predicted on the basis of a type of collision of the second kind resulting in ionization of atoms by collisions with ions of atoms of higher ionizing potentials. These processes are represented by the following equations:

$$He^+ + H_2 = He + H_2^+ \qquad He^+ + N_2 = He + N_2^+$$
$$Ne^+ + H_2 = Ne + H_2^+ \qquad Ne^+ + N_2 = Ne + {}^{17}N_2^+$$
$$Ne + {}^{34}N_2^+ = Ne^+ + N_2$$
$$A + H_2^+ = A^+ + H_2 \qquad A + N_2^+ = A^+ + N_2$$

In these cases as in pure rare gas mixtures the interchange was found to be most probable when the difference between the ionizing potentials was least.

23. The dissociation of hydrogen chloride by positive ion impact. WALTER M. NIELSEN, Duke University.—Positive ions from a heated sodium phosphate source were projected between two electrodes, P_1 and P_2, towards a third electrode, P_3. The hydrogen chloride, fed into the tube through a fine capillary, was generated by dropping H_2SO_4 onto NaCl. With a mean free path of about 2cms, and with a potential on P_1 such as to prevent positive ions from reaching it, and with a small drawing out potential for positive ions on P_2 and P_3, currents were measured for increasing values of the driving potential, V_F. No negative current to P_1 was observed below 34 volts. Above this value of the driving potential the ratio of negative current to total positive ion current increased rapidly with increase in the driving potential. The positive currents were of the order of 1×10^{-9}amperes, the negative of the order of 2×10^{-10}amperes. A magnetic field of about 500 gauss was applied so as to prevent secondary electrons from leaving any of the accelerating or collecting electrodes. The driving potential at which a negative current is first observed is lowered by an increase in the drawing out potential of P_2 and P_3, but is not affected by an increase in the retarding potential of P_1. The experiment does not indicate the products of dissociation.

24. Combination of hydrogen and oxygen by electric discharges and x-rays. ROGERS D. RUSK, North Central College.—A study has been made of the combination of hydrogen and oxygen in the Geissler tube discharge, low-voltage arc, electrodeless discharge and by exposure to x-rays. Rates of combination were measured at pressures varying from 1mm to .01mm and with different proportions of the gases. In the low-voltage arc, the rate of combination per milliampere of arc current was abnormally small after making due allowance for the catalytic action of the coated platinum filament, which set in quite regularly with the filaments used at 65°C (thermocouple measurement.) This suggests that in the low-voltage arc combination occurs mostly at or near the cathode. The logarithmic decrease in rates of combination in the other cases indicates that combination is a matter of gaseous collision. The results agree with the notion that combination is proportional to number of ions present, and in the Geissler tube discharge approximately 0.12 molecules of water per ion were formed at a pressure of .1mm in equivalent volumes.

25. The dissociation of hydrogen by electrons. A. L. HUGHES and A. M. SKELLETT, Washington University.—The dissociation of hydrogen, through which electrons are driven, may be the direct result of a collision between an electron and a hydrogen molecule, or it may be due to a secondary process, in which the dissociation actually results from a collision between a neutral hydrogen molecule and an ionized (or excited) molecule which itself had been produced by an electron impact. At sufficiently low pressures, the number of molecules dissociated should be proportional to the pressure if the effect be a direct one, but proportional to the square of the pressure if the effect be a secondary effect. Using the yield of dissociated hydrogen molecules at different pressures as a criterion, the experiments are decisively against the effect as being a secondary effect. Investigation shows that if the mean free path of the ionized (or excited) molecule be abnormally small, the above criterion may not be able to distinguish between the two possible processes at pressures available. Provided that the mean free path is not less than one three hundredth of that of the normal molecule, these experiments are decisively against the interpretation that dissociation is a secondary process.

26. Some observations on the nature of the nitrogen afterglow. A. G. WORTHING, Nela Research Laboratory and University of Pittsburgh.—Three 6-inch spherical glass bulbs symmetrically joined by large glass tubing were filled with nitrogen (1 to 5mm). Discharges in one bulb caused sudden visible streamings to the other bulbs. After the filling of the bulbs, the afterglow stream, which was produced by a single impulsive discharge, was completely stopped near the exit. It formed an umbrella-shaped luminous cloud which was many times as bright as the afterglow elsewhere in the bulb. After many discharges, the resistance to the passage of the afterglow broke down, and the afterglow carriers seemed to pass unhindered to the other bulbs. The most probable explanation suggests either that the afterglow carriers or that some of the agents active in the production of these carriers are electrically charged.

Some experiments with a tube (approximately 200mm of A, 0.4 mm of N_2) seem to indicate that this effect is limited to the early stages following a discharge. These observations do not seem to support the view that the afterglow has its origin in impacts of neutral unexcited nitrogen atoms and molecules.

27. The scattering of electrons by a nickel crystal. C. DAVISSON and L. H. GERMER, Bell Telephone Laboratories, Inc.—In bombarding a $\{111\}$ surface of a single crystal of nickel with a beam of electrons of uniform speed it has been found that, for certain definite bombarding speeds, there are beams of scattered electrons leaving the crystal in perfectly sharp directions. A simple correlation between these directions and the directions taken by diffracted beams of x-rays can be stated as follows. If the known crystal structure of nickel were contracted by a factor of 0.7 in a direction parallel to the incident beam then among all the diffracted x-ray beams those ten sets of beams which correspond to the longest x-ray wave-lengths would coincide in position with ten observed sets of electron beams. The wave-lengths of the wave disturbances which could give rise to these beams are quite accurately given by $\lambda = h/mv$, in accordance with the wave mechanics. In addition to these ten sets of electron beams there are three other such sets for electrons below 200 volts. These three sets seem not to observe the symmetry required by the known structure of the nickel crystal, and they offer strong evidence that there exists in this crystal a structure which has not been hitherto observed for nickel.

28. O- and N-energy levels in the secondary emission of hot tungsten. HERMANN E. KREFFT, General Electric Company, Nela Park.—While critical potentials found by Richardson and Chalklin in the soft x-radiation of tungsten agree fairly with computations of its O and N-energy levels from x-ray data, there does not seem to be such a relation between these levels and breaks found by Petry on the secondary emission curve. If, however, the secondary emission is measured with the tungsten at about 1200° K, a number of breaks are easily obtained at primary velocities of $v_p = 5$ to 750 volts on the curve showing the number of secondary electrons per primary as a function of v_p. The electrode arrangement is similar to the one described by Petry. A very considerable break occurs at a primary velocity of 70.5 volts (corrected), this one also being the most prominent break above 25 volts. With cold tungsten only a slight indication of this break is obtained. This break is undoubtedly due to the O_I-level of the tungsten atom, the value 70.5 volts, or $\nu/R = 5.2$, being in excellent agreement with the value given by Bohr and Coster. The greater part of the other breaks agree well with measurements of Richardson and Chalklin and with the values for the N_I, N_{II} and N_{III} levels computed by Nishina. The secondary emission of other metals near tungsten will have to be studied before a definite interpretation of these breaks can be made. This work is being continued.

29. Reflection of electrons from molybdenum. W. R. HAM, Pennsylvania State College.—The apparatus in use consists of: (1) a source of steady direct current; (2) water-cooled Coolidge tubes with molybdenum anti-cathodes; (3) a constant flow calorimeter for measuring the heat developed at the anti-cathode; (4) a method of applying retarding potentials varying from zero to full impressed p.d. to the outside surface of the glass of the tube, while the tube is being run at a particular impressed voltage. (1000–22,000 volts). Since the power input, the heat generated at the anti-cathode, and the velocity distribution of reflected electrons are all measured, the percent of reflected electrons relative to incident electrons may be plotted against velocity of reflected electrons. A large percentage of reflection occurs at velocity corresponding approximately to 2900 volts. Peaks of reflection seem to occur as the impressed p.d. passes the critical potentials for the L levels and also probably the K level of molybdenum. The total number reflected is in general more than 100 percent of the incident electrons but much the larger part of this number have relatively slow velocities. Different tubes behave much alike and there is little evidence that residual gas has any effect on the results.

30. Velocity distribution and 180° scattering of low velocity electrons from iron. H. E. FARNSWORTH, Brown University.—The curve expressing ratio of secondary to primary electron current as a function of accelerating potential for both iron and copper show prominent

maxima and minima in the low velocity region. If these are due to atomic inelastic collisions one might expect to find evidence of this from a measure of the velocity distribution of the secondary electrons. Such measurements for iron show no evidence of inelastic collisions. These results, together with the fact that the above mentioned maxima and minima are obtained only after heating the metal at a critical temperature, are interpreted to mean that sudden changes in slope in the low velocity region of the secondary electron curve for metals are not an atomic phenomenon but are characteristic of the arrangement of atoms at the surface. The apparatus was such that those electrons leaving the iron target nearly normally, fell on an insulated disk concentric with the primary beam thus giving a measure of the fraction leaving approximately normally. This fraction, for primary velocities of a few volts, is much greater than that to be expected from the cosine distribution law, and decreases rapidly with increasing primary velocity to about 30 volts. Observations subsequent to baking the target at 350° C but previous to heating at red heat did not show this distribution.

31. A theory of the normal cathode fall. K. T. COMPTON and P. M. MORSE, Princeton University.—Use is made of the experimental value of the cathode fall of potential V_n and Townsend's empirical equation for the number of ionizing collisions α per unit path by an electron, together with the principle that the potential drop is distributed throughout the fall space so as to give maximum current. Thence is deduced the law $pd_n = A$ for the product of the pressure p and cathode fall space d_n, and acceptable values of the constant A are calculated for various gases. Certain dependence of d_n on cathode material is predicted, in conformity with observations. Distribution of ionization throughout the fall space is also calculated, and the results prove that a cathode in an ionized gas must be a much more copious emitter of electrons under positive ion bombardment than is a degassed metal. Introduction if Poisson's equation leads to the known law for normal current density $(j/p)^{1/2} = B$, and gives values of B which are approximately correct. At several points second order corrections are neglected, and the boundary conditions are not very satisfactorily known. Yet the theory seems to be distinctly promising in this field, in which there has been no previous tenable theory.

32. Heats of condensation of electrons and positive ions on molybdenum. C. C. VAN VOORHIS and K. T. COMPTON, Princeton University.—A small molybdenum sphere was supported in a region of intense gas ionization by three fine wires, two of which formed a thermocouple to measure its temperature, while the third carried the current of the incoming ions. Space potential and mean electronic energies $\bar{v}$ were found by using the sphere as an exploring electrode. Its rate of heating due to an increment Δi in the electron current reaching it against a small retarding field was measured and equated to $\Delta i(\bar{v}+\phi)$, whence the heat of electron condensation ϕ was found to be 4.76 volts in argon; 4.77 or 5.01 volts in nitrogen; and 4.04 or 4.35 volts in hydrogen. The double values follow different treatments of the surface. The probable error of measurement is less than 1 percent, but uncertainty regarding the specific heat of molybdenum causes some uncertainty in the absolute values. Similar measurements of the heating effect of a positive ion of argon gave about one volt, which indicates that less than half of the energy of neutralization of the gas ion at the surface, is absorbed by the metal. ϕ_- and ϕ_+ are involved in the theory of gas discharges. Incidentally, confirmatory evidence was found for Langmuir's "high speed electrons."

33. The method of least squares vs. the arithmetic method of obtaining the slope of a straight line. R. C. SPENCER, Westinghouse Lamp Company, Bloomfield, N. J.—This discussion applies particularly to the case where the abscissas are spaced equidistantly. To illustrate: Let $t_1, t_2, \cdots, t_r, \cdots, t_s, \cdots, t_N$ be the times of N transits of a torsion pendulum. Let the difference, $(t_r - t_s) = T(r-s)$, have a weight of unity. Then the period, $T = (t_r - t_s)/(r-s)$, will have a weight of $(r-s)^2$ because the error in $(t_r - t_s)$ has been divided by $(r-s)$. In general we will use only n observations, discarding the inner ones. The weight of the period as calculated by the method of least squares is $(N-1)^2+(N-3)^2+(N-5)^2 \cdots$ to $\frac{1}{2}n$ terms. The weight of the arithmetic solution is $\frac{1}{2}n(N-\frac{1}{2}n)$. The arithmetic method has a maximum weight when the inner third of the observations are discarded. Tables are given comparing the two methods.

The arithmetic method can be used on a standard motor driven calculating machine by pressing the numbers 1, 2, 3 etc. up to $n/2$ and down again to 0. The sum will give the period, T, in fifths of seconds times $\frac{1}{2}n(N-\frac{1}{2}n)$. A mechanical spring model is described. The potential energy at equilibrium is a minimum, and is proportional to the sum of the squares of the spring displacements. Therefore, the equilibrium position gives the least square solution of the system.

34, Log, semi-log, and uniform coördinator. II. R. A. CASTLEMAN, JR., Bureau of Standards.—A log, semi-log, and uniform *coördinator*, (a combination of plotting instrument and computing instrument) has been designed with special reference to its usefulness in the physics or physical engineering laboratory. The device employs a drawing board, a T-square, two slide rules and certain machined accessories. One rule is attached along one edge of the drawing board, while the other is attached to the T-square, whose shoe is arranged to bear on a straight-edge of the former slide-rule. Indices attached to the T-square and a suitable slider make possible: (a) coordination of the three kinds mentioned above; (b) quick and easy change from plotting to computing; (c) quick and easy change from one side of the T-square blade to the other. Each rule carries three sizes of log and one of uniform scales, thus furnishing practically all needed combinations. The use of a somewhat similar device in the special cases of power and exponential-finding has been pointed out in previous articles.

35. Shielding from vibrations. R. C. HARTSOUGH, Western Electric Company, Inc.—The shielding of sensitive apparatus from vibration by the use of thin inflated rubber bags has been found to approach 100 percent. Three bags are generally used and interconnected so that they all have exactly the same pressure. A pressure of 50cm of water and approximately four pounds mass on each bag gave perfect shielding for all ordinary vibrations. An interferometer mounted on a quartz fibre was shielded so effectively that the fringe system was quiet, even with persons walking in the room.

36. A redetermination of the Newtonian constant of gravitation. PAUL R. HEYL, Bureau of Standards.—The present accepted value of the Newtonian constant of gravitation rests upon the independent work of Boys and Braun done thirty years ago. It is 6.66×10^{-8}, with an uncertainty of one unit in the third significant figure. About three years ago the Bureau of Standards undertook a redetermination of this constant with the object of obtaining another decimal place. The results so far obtained confirm the present accepted value and add the desired figure 6.664. The method was that of a torsion pendulum in a vacuum, as used by Braun.

37. A resonance method for the determination of the universal constant of gravitation. JACOB KUNZ, University of Illinois.—Two comparatively large spheres placed on a table are made to carry out undamped simple harmonic motion. Between these spheres there are suspended two small spheres, connected by a light bar, in a vacuum. The harmonic motion of the outer spheres induce forced oscillations of the inner spheres, which become large when their natural frequency coincides with the impressed frequency. The differential equation of the motion has been developed. It is much more complicated than the classical differential equation of resonance. The present differential equation has been solved by a method of successive approximations.

38. Variation of gold plated screw-knob weights with atmospheric humidity. A. T. PIENKOWSKY and E. S. FOWLE, Bureau of Standards.—Many gold plated weights of the common screw-knob type have been found to change by excessive amounts with changes in the humidity of the air. Measurements were made on the sum of the weights from 1 gram to 50 grams inclusive, from each set. When the relative humidity changed from 30 percent to 70 percent, the worst set yet noted changed nearly 3 mg in 8 days, and was still gaining rapidly. When the humidity was lowered to 30 percent again, these weights promptly returned to their original value. In the 18 sets first tested, more than half the sets changed more than 0.5 mg for the same

conditions, while about 0.1 to 0.2 mg seems to be the smallest change that occurs with such sets. These weights were from both American and foreign makers. Several variable sets were boiled in water with the knobs out and with the adjusting material removed so far as practicable. The variations then dropped to about 0.2 mg. Weighings were made without removing the sets from a box in which the humidity was controlled, but the standards and balance were outside this box, and therefore not affected by the changes in humidity.

39. Thermal expansion of some nickel steels. PETER HIDNERT and W. T. SWEENEY, Bureau of Standards.—Data on the linear thermal expansion of some nickel steels containing from 36 to 42 percent nickel, have recently been obtained for various temperature ranges between room temperature and 500°C. The expansion curve of each steel showed a critical point by an abrupt increase in the rate of expansion. The nickel steels containing from 38.4 to 42.2 percent nickel expand less than invar for the temperature range from 20° to 500°C. Additional alloys having a greater range of coefficients are being tested. The following table gives a comparison of the results obtained.

Nickel Content Per cent	Critical Point °C	Average Coefficient of Expansion per Degree Centigrade: 20° C to Critical Point $\times 10^{-6}$	Average Coefficient of Expansion per Degree Centigrade: Critical Point to 500° C $\times 10^{-6}$
36.4	260	3.1	14.4
36.9	260	3.3	14.7
38.4	300	3.5	14.4
41.0	340	5.1	14.2
42.2	340	5.5	13.6

40. The resolving power of the ears. ARTHUR LOWELL BENNETT, Union College. (Introduced by P. I. Wold.)—The resolving power of the ears will be defined for use here as the shortest time interval between two successive sound impulses, the first occurring in one ear and the second in the other, for which interval the observer can distinguish in which ear the first impulse occurred. When the interval becomes quite small the sounds merge into each other but, through the binaural sense, one is still made aware of the difference in time of arrival. A rotating disc with two brush contactors, one of which could be displaced angularly, made it possible to send two impulses separated by a small time interval measurable to a hundred thousandth of a second. Data taken on eleven observers show that every observer was able to distinguish with certainty at one one-thousandth of a second and that the limit for the average observer is one tenth of this or less. One exceptional observer was found whose limit was less than one millionth of a second.

41. The surface tensions of the molten elements as functions of the temperature. I. Copper. E. E. LIBMAN, National Research Fellow, University of Illinois.—Copper is melted in a square box with a capillary side tube by means of a high vacuum, water cooled, molybdenum wound furnace of special design. The temperature is measured by means of the resistance of the molybdenum furnace winding. An x-ray photograph is taken through the entire furnace and the capillary depression and depression of the surface at the walls of the square box is measured on the photographic films. This gives two observations for the two unknowns, surface tension and angle of contact. The method, as usual, gives not the surface tension directly but the capillary constant" (twice the surface tension divided by the product of the density of the molten material and the acceleration of gravity) from which the surface tension can be obtained when the density of the molten material is known. In this way the capillary constants of copper have been determined over a range of temperature from the melting point 1083°C to about 1400°C, and the error is estimated not to exceed 2 percent. The capillary constant of copper at its melting point is .301 cm^2 and decreases linearly with rise in temperature to .269 cm^2 at 1375°C.

42. Variation of surface tension of oils with the temperature. GEORGE WINCHESTER, Rutgers University.—The surface tension of several high flash point oils has been measured at temperatures up to 550°F during the last two or three years by the maximum bubble pressure

method. The densities of the oils were linear functions of the temperature up to 450°F. Between 300° and 550°F Mendelejeff's equation for an ideal liquid is verified within the limits of experimental error, estimated at about 0.4 of a dyne. Below 300°F the surface tension decreases faster than the temperature rises. The critical temperature is calculated from the formula, $T=a-bt$.

43. Influence of electrolytic ions upon moisture of steam. (Analogue of Wilson cloud experiment.) ARTHUR W. EWELL, Worcester Polytechnic Institute.—Bubbles of vapor, breaking at the free surface of a liquid, inevitably throw some liquid into the vapor space and, if the vapor is continuously drawn away, some of this liquid will accompany the vapor—a phenomena known technically as "priming." An apparatus was designed, which permitted quite accurate measurements of the priming of pure water, and of various solutions. It was found that priming increases with the density and viscosity of the solution, and decreases with the number of electrolytic ions present. The addition to water of such a salt as sodium or potassium chloride, which highly dissociates, and increases the density and viscosity but little, reduces the priming. As gaseous ions in a vapor facilitate the formation of liquid bubbles, so electrolytic ions in a liquid (probably by reduction of surface tension) facilitate the formation of vapor bubbles, and thus produce quieter boiling and less priming. Slightly dissociated salts, such as lead acetate, increase the priming on account of the large increase which they produce in the density, and solutes showing no dissociation, such as cane sugar, increase the priming still more.

44. Relations in connection with the reversible mixing of substances in the condensed state at the absolute zero of temperature. R. D. KLEEMAN, Union College.—The properties of the quantities associated with the reversible mixing of substances in the condensed state, initially under the pressure of their vapors at the absolute zero of temperature, have been investigated on the basis of the theoretical results previously communicated (Phys. Rev. **29**, 369 (1927)). It is shown that: $H_m=0$, $(\partial H_m/\partial T)_v=0$, $(\partial^2 H_m/\partial T^2)_v=0$, $(\partial H_m/\partial T)_p=0$, $(\partial^2 H_m/\partial T^2)_p=0$, $dH_m/dT=0$, $d^2H_m/dT^2=0$, $p_m=0$, $(\partial p_m/\partial T)_v=0$, $(\partial^2 p_m/\partial T^2)_v=0$, $(\partial p_m/\partial T)_p=0$, $(\partial^2 p_m/\partial T^2)_p=0$, $dp_m/dT=0$, $d^2p_m/dT^2=0$, $A=0$, $(\partial A/\partial T)_v=0$, $(\partial^2 A/\partial T^2)_v=0$, $(\partial A/\partial T)_p=0$, $(\partial^2 A/\partial T^2)_p=0$, $dA/dT=0$, $d^2A/dT^2=0$, where H_m denotes the heat absorbed during the process of mixing the substances, A the external work done, p_m the increase in internal energy, p the pressure, v the volume, and T the absolute temperature. A total differential coefficient indicates that the substances are kept under the pressures of their vapors during a change in temperature. Accordingly the mixing of substances, including different forms of the same substance, is under these conditions not attended by a change in entropy and internal energy. The formulas: $T\Delta S=H_m=p_m+A=\Delta U+A$, $\Delta U=T(\partial A/\partial T)_v-A$, $\Delta U=T(\partial A/\partial T)_p-A$, $\Delta U=T(dA/dT)-A$, it can then be shown, hold for all temperatures, where S denotes the *controllable* entropy and U the *controllable* internal energy.

45. The vacuum tube oscillator. D. G. BOURGIN, Lehigh University.—The functional dependence of total filament emitted current on grid and plate voltages is formally approximated by $i_p+i_g=A[1-\exp\{-(E_p+\mu E_g)^2\}]$ for $E_p+\mu E_g>0$ where A is the saturation value of the current and the other symbols are standard notation. (The approximation may be improved by considering this to be the initial term in an expansion in terms of Hermite polynomials). This relation is made the basis for the "second order" treatment of the Hartley oscillator. By applying Kirchoff's laws to the equivalent network, three simultaneous differential equations of the third order are derived connecting the variable grid and plate voltages and currents, and the current in the oscillatory circuit. These equations are restricted to the case that the phase difference between E_p and E_g is closely 180° and that the general conditions for efficiency indicated by Prince are satisfied. Only the fundamental is considered. By tabulating the values of the Fourier series coefficient for the fundamental in the expansion of $\exp\{-(a+b\sin x)^2\}$ it becomes possible to use a combined analytical and graphical method to determine the amplitudes, phase relationships and fundamental frequency. The approximation for the grid current is, as yet, not wholly satisfactory.

46. A device to draw characteristic curves of vacuum tubes automatically. G. C. CAMPBELL and G. W. WILLARD, University of Minnesota.—The usual circuit for obtaining characteristic curves was used. The grid-potential was varied continuously throughout the desired range by a modified W. G. Pye drum rheostat of the potentiometer type driven by a synchronous motor through speed reducing gears. A Leeds & Northrup recording pyrometer of the potentiometer type, connected across a standard resistance in the plate circuit, automatically drew the grid-potential plate-current curve in rectangular coordinates. The paper roll of the recording instrument was driven by the same motor that varied the grid-potential in order to insure uniformity. The instrument worked well with currents as low as 0.5 milliampere for full scale deflection which interpreted graphically means the maximum ordinate permitted by the width of the coordinate paper which was ten inches. Obviously, smaller currents require a larger resistance in the shunt to give sufficient potential drop for full scale deflection which reduces the sensitivity of the instrument and fixes the low current limit for satisfactory operation with any given glavanometer in the recording instrument. Characteristic curves of a higher order of accuracy than are usually obtained by plotting points were drawn in from five to ten minutes depending on the reducing gears used.

47. Space charge as a cause of negative resistance in a triode. LEWI TONKS, General Electric Co.—Oscillations occurring in a tuned circuit connected to grid and plate of a triode have been obtained by Gill (Phil. Mag. **49,** 993, (1925)) when the grid potential was 40 volts and plate potential 8 volts. These were ascribed to unstable space charge in the tube. In the present paper the mathematical theory for the case of plane parallel electrodes is first presented and later applied qualitatively to the case of cylindrical electrodes. The existence of a virtual cathode may cause negative resistance in both plate and grid circuit under emission limited operation, but for the case of space charge limited operation negative resistance is at most very small. The theory has a possible bearing on very short wave generation by the method of Barkhausen and Kurz (Phys. Zeit. **21,** 1 (1920)).

48. Electric absorption currents in solid dielectrics. HUBERT H. RACE, Cornell University. (Introduced by F. K. Richtmyer).—The lower electrode of a guard-ring condenser containing specimen under test was connected, either (A) to constant potential or (B) to ground. The upper electrode was connected to a quadrant electrometer and an adjustable air condenser. This insulated system was maintained at ground potential by controlling voltage on the air condenser. Thus charge, (A) and discharge, (B), curves were obtained as functions of time (t). Using plates in intimate contact with specimen, potential was applied until current became constant at I_c, the true conduction current. Then potential was removed and the following relation was observed for certain materials: $i(\text{charge}) - I_c = -i\,(\text{discharge}) = i_a$ (1). For these materials, of which hard rubber is a good example, an approximate straight line was obtained between log i_a and log t, so that the current i_a, due to absorption, may be represented by the equation: $i_a = (c/t)^b$ (2) where b and c are determinable constants. Tests were also made with an air gap between specimen and upper plate. Eq. (2) was still found true but eq. (1) was not.

49. Effect of temperature on polarization capacity and resistance for gold and platinum electrodes in different concentrations of sulphuric acid and at different audible frequencies. E. E. ZIMMERMAN, Cornell University.—Measurements of polarization capacity together with corresponding values of cell resistance have been made for gold and platinum electrodes in sulphuric acid solutions at temperatures varying from 0°C to about 90°C. Measurements were made by means of an a.c. bridge using frequencies from 650 to 3900 cycles. For platinum electrodes in a 12.7 percent solution of H_2SO_4, the temperature coefficient is positive and has a value of about 0.37 of a microfarad, for one electrode of unit area, per degree rise in temperature. The value decreases at the upper range of temperatures and also with decreasing concentration. For gold electrodes, the average value of the temperature coefficient is about one-tenth of that for platinum. In contrast to the results with platinum, the value of temperature coefficient increases at the upper part of the temperature range. Cell resistance, with platinum electrodes, decreases with increasing temperature while with gold electrodes the

resistance, especially at higher temperatures, increases with temperature. For both metals, the temperature coefficient of capacity decreases with increasing frequency. Incidentally, studies of variation of capacity and cell resistance with varying frequency have been made at constant temperature. Also, decay curves have been obtained for gold electrodes after hydrogen polarization. No such decay curve could be obtained using platinum electrodes.

50. Analysis and applications of wave filter determinants. FRANCIS D. MURNAGHAN and HAROLD A. WHEELER, Johns Hopkins University.—In the study of the electric wave filter comprising a finite line of recurrent sections, the simultaneous equations in currents and voltages yield determinants of a known type. By the method of difference equations, various typical determinants are evaluated and expressed in terms of convenient substitutions. Special attention is given to the finite cases involving (1) terminal conditions and (2) two recurrent sections in alternating succession. Procedures are given and simple formulas developed applying the determinants to (1) free oscillation frequencies of finite, conservative lines and (2)steady state response of finite, non-dissipative Campbell filters, terminated by any values of resistance, as a function of the frequency of the applied alternating voltage. Proceeding to the infinite line by a novel method, the iterative impedance and propagation exponent are derived. The definition of complex electric impedance is outlined to show the fundamental differential equations involved and thereby make the work equally applicable to other systems with similar differential equations.

51. Formal unification of gradient, divergence, and curl, by means of an infinitesimal operational volume. VLADIMÍR KARAPETOFF, Cornell University.—Besides the usual definitions of gradient, divergence, and curl, familiar to physicists, some German writers on Vector Analysis (Runge, Spielrein, von Ignatowsky) define these quantities as ratios of certain integrals of a scalar or vector function, taken over a small closed surface, to the volume comprised within the surface, when both tend to the limit zero. By properly choosing the *shape of an infinitesimal operational volume*, around the point under consideration, and its *position with respect to the lines of force, integrations can be done away with, and it is not necessary to reduce the results to the limit zero.* The above operators thus become symbols for certain forms of *space derivatives*, independent of fixed axes of coordinates. The results throw additional light on the *physical nature* of divergence and curl. The operational volume may be so chosen and placed as to give the *total magnitude of the curl vector*, and not only its components.

52. Surface layers produced by activated nitrogen. CARL KENTY and LOUIS A. TURNER, Princeton University.—A one mil tungsten wire at about 450°C placed in a stream of nitrogen shows a large decrease in resistance when the active nitrogen produced by a condensed discharge reaches it. The same effect is produced by bombarding still nitrogen in the neighborhood of the filament with electrons. In a tube having a large nickel anode the minimum accelerating voltage for producing a detectable effect is 10.8 volts but it is considerably higher (about 21 volts) in a tube having a hot tungsten filament anode. The decrease of resistance is attributed to the formation of a surface layer which increases the emissivity of the filament, thereby lowering its temperature. The effect increases with the pressure in the range from 0.04 to 5 mm. The film is removed by flashing the filament or pumping out the gas. The effect is apparently produced by a neutral substance, being independent of the potential of the test filament. Active nitrogen also causes a large reduction of the thermionic current from a tungsten filament. Such an effect is obtained with ordinary nitrogen in the hot anode tube, a saturation current reached at 15 volts being reduced at voltages above 21.

53. Simultaneous ionization and excitation of molecules on collision with foreign ions. O. S. DUFFENDACK and H. L. SMITH, University of Michigan.—The spectrum of a low-voltage arc in a mixture of 90 percent helium and 10 percent CO contains the Comet Tail, First Negative, and Baldet-Johnson bands of CO^+ strongly developed. In neon and CO the Comet Tail bands are strong, the First Negative weak, and the Baldet-Johnson absent. None appear in an argon-CO mixture. The introduction into the discharge of twice as many electrons from an auxiliary filament as from the cathode failed to increase the intensities of the bands if their

accelerating voltage was less than the ionizing potential of the rare gas, even though it was above the excitation potential of the bands. Hence these bands were not excited by electron impacts either upon the CO^+ ions or upon the CO molecules. To determine whether excited atoms or ions were effective in producing these bands, nitrogen was substituted for CO. Its negative bands appeared strongly in helium and in neon mixtures. As their excitation potential is above the strong radiating potentials of neon, their excitation must be due to the ions. We conclude that an ion may ionize a molecule and excite the resulting ion to the degree the ionizing potential of the one exceeds that of the other.

54. Residual ions and critical restriking potential in mercury arcs. M. L. POOL, University of Chicago. (Introduced by A. J. Dempster).—Using as a collector for electrons a 4 mil wire and for positive ions an anode which completely surrounds a hot cathode the rate of removal is given by $n = n_0 e^{-kt}$ where $k = 240$ for all voltages during the first 1/75 sec. After 1/300 sec the space charge sheaths about the anode and wire are 2 mm in thickness and 1 mm in radius respectively. These sheaths rapidly expand in size and within 1/50 sec. fill the entire arc space. Replacing the wire by a larger collector the arc space has been swept free of ions within 1/500 sec. The restriking of a mercury arc at the lowest radiating potential is explained by means of the large concentration of electrons and ions which exist near the filament. There electrons will have energies up to 5 volts. When the arc is stopped these electrons will diffuse into the filament and in order to repel them the filament must be made 5 volts negative with respect to the gas. If the filament is made still more negative electrons can leave the filament and the arc restrikes through ionization of the metastable atoms formed by continual recombination.

55. The fine structure of the mercury line 3650 A. W. H. MCCURDY, National Research Fellow, Johns Hopkins University.—The fine structure of the Hg line 3650 A has been studied by means of crossed Lummer-Gehrcke plates of quartz. The results show that this line consists of five components within the limits of the observations. The separations are -45, -32, -20, 0, $+102$ mA. The main component is found to be single within the limits of the plates but under certain arc conditions it is found to appear reversed. Nagoaka, Siguira and Mishima have studied all the strong lines of the mercury arc spectrum and they give as the structure of the main component a group of three lines with weaker ones on each side. The structure of the main component in their results may be due to broadening of the line and partial reversal due to the type of arc used. It is possible that their results on the line 2967 A may also be incorrect for the same reason, as the main component of this line also shows absorption under some conditions. This shows the importance of the source in fine structure work.

56. Zeeman-effect of the fine structure components of λ 2536 of mercury. WALTER A. MACNAIR, National Research Fellow, Bureau of Standards.—Preliminary results of an extended study of the Zeeman-effect of λ2536 of mercury show that the five fine structure components split into triplets, the perpendicular components of which behave as the perpendicular components of 322 normal triplets with no Paschen-Back effect in fields up to 5000 gauss, the present limit of the magnet being used. The parallel or central components of the five triplets show some pecularities in fields of 3000 gauss and over.

57. H_3 as a possible emitter of the secondary hydrogen spectrum. CHARLES J. BRASEFIELD, Princeton University.—Positive ray analysis of the ions in a discharge in hydrogen show that H_3^+ is by far the predominant ion, except at very low pressures. In an attempt to correlate the proportion of H_3^+ with the intensity of the lines of the secondary spectrum, photographs were taken of the discharge operated under two different conditions; (1) In which no H_3 ions were detectable and (2) in which the number of H_3 ions was quite appreciable. The second type discharge showed marked enhancement of the Fulcher bands in the red and blue, which was at first attributed to H_3. However, when the electron velocities were determined by the Langmuir exploring electrode method, and the results compared with the curves obtained by Lowe showing the variation of intensity of the secondary lines with the energy of

the exciting electrons (Trans. Roy. Soc. Canada, **20**, 217 (1926)) it was found that the observed change in intensity could adequately be accounted for by change in electron velocity. Very little evidence was found to support the bands recently found by Allen and Sandeman which they ascribe to H_3.

58. Theory of the Stark-effect in the arc spectra of helium. J. STUART FOSTER, McGill University, Fellow of the International Education Board (in Copenhagen).—In this application of the perturbation theory of the quantum mechanics of Heisenberg quantitative displacements and intensities replace the less definite qualitative explanation afforded by the correspondence principle in the earlier Bohr theory. Following Kramers, the hydrogen atom is considered to be perturbed by (1) an inner and entirely central field which effectively replaces the time mean position of the inner helium electron as well as its resonance action, and (2) a uniform external electric field. As a first approximation, the perturbation matrix $H_1(n, m, k)$ therefore contains, within a region of given n and m, (1) diagonal terms which denote the differences (at zero field) between the hydrogen and the parhelium (or the orthohelium) spectral terms identified by the various k values, and (2) terms due to the applied field, and identical with those recently given by Pauli and by Schroedinger in the theory of the Stark-effect in hydrogen. The various Stark patterns as well as great variations in the displacements and intensities previously observed by the writer over a wide range of field strengths are faithfully reproduced in the theory. An interesting feature in accord with the observations is the vanishing of a few components at certain field strengths and their reappearance at higher fields. Displacements of the following line groups have been calculated at seven field strengths: λλ 4922, 4388, 3965, 3614, 4472, 4026, 3188, and 2945. The intensities have been calculated at 10, 40, and 100 kv/cm.

59. The light absorption of liquefied gases. F. G. BRICKWEDDE and W. A. MACNAIR, Bureau of Standards.—For the study of the absorption of liquefied gases, the continuous spectrum of hydrogen was used for wave-lengths 2000–3700 A, a bromine cell cutting out wave-lengths greater than this, and the light from an incandescent bulb was used for wave-lengths 3400–6500. The absorption spectra were photographed with a Hilger E2 quartz spectrograph. The liquefied gases were contained in a cylindrical, quartz Dewar flask—inside diameter 22 mm—mounted in front of the slit of the spectrograph. The results obtained with liquid oxygen were found to be in essential agreement with the results published by W. W. Shaver (Trans. Roy. Soc. of Canada, **15**, 7 (1921)), except for a number of new bands not previously recorded. Three of these obviously belong to the system of broad bands found by Shaver, extending between wave-lengths 2600 and 2800. No absorption was found in liquid nitrogen between wave-lengths 2000 and 6500, and no absorption in liquid hydrogen between wave-lengths 2000 and 3800.

60. Reproducible liquid filters for the determination of the color temperatures of incandescent lamps. RAYMOND DAVIS and K. S. GIBSON, Bureau of Standards.—A series of filters has been devised, reproducible from specification, by means of which any Planckian energy distribution from 2300° to 4000°K may be converted to the color of mean Washington sunlight. Given a simple photometer, a lamp standardized at some one temperature in the above range, and the proper filter, a second lamp may then be calibrated at as many temperatures as is desired by preparing the respective filters. The solutions required for any given filter are contained in a two-chamber glass cell, one chamber containing a one-centimeter thickness of an aqueous solution of copper sulphate, pyridine, and mannite, the other, a one-centimeter thickness of an acidified aqueous mixture of copper sulphate and cobalt ammonium sulphate. Careful spectrophotometric measurements from 350 to 750 mμ were made on medium concentrations of the three component solutions, and the validity of Beer's law studied over the range of concentrations necessary. The respective concentrations were then varied until the color characteristics of the source-and-filter combinations were, by computation, all identical with that for mean sunlight.

61. The fluorescence of sodium vapor. R. W. Wood and E. L. Kinsey, Johns Hopkins University.—Sodium vapor contained in a Wood sodium tube was excited by monochromatic radiation in the blue-green region obtained by sunlight and a monochromater. Although the exciting radiation corresponded only to a molecular absorption band group in the blue-green region and to no absorption lines in the sodium atom, the "D" lines appeared in the fluorescence spectrum when the pressure of the residual gas was around 4 mm. The phenomenon was not obtained at lower or higher pressures. Bands appearing in the region surrounding the "D" lines in the fluorescence spectrum under white light excitation were studied. They have been definitely determined to appear only at pressures of the residual gases (hydrogen and nitrogen) around 6 mm. Approximate monochromatic excitation shows them be to excited only by wave-lengths in their own region. Absorption spectra obtained with both a two meter and twenty foot spectrograph so far fail to reveal these bands. The introduction of small quantities of potassium failed to effect the appearance of these bands.

62. Spark spectrum of nickel. A. G. Shenstone, Princeton University.—The following terms of Ni II have been identified:—1. Low set in order $^4F'$, $^2F'$, $^4P'$, $^2P'_2$, ^{2}D all from the structure d^8s. 2. Intermediate set (d^8p) ^{4}D′, ^{2}D′, $^4G'$, $^2G'$, ^4F, ^2F; $^4S'$, ^4P, ^{4}D′ and a large number of levels unidentified. 3. A high $^4F'$, $^2F'$ (d^8, s). These terms account for about two-thirds of the lines including practically every strong line. Zeeman effects indicate that the g-values of $^4F'$, $^2F'$ and the corresponding intermediate triad are probably regular. The g-values of $^4P'$ etc., are certainly irregular as are also the intervals. All terms are inverted except that $^4G_6$ is higher than $^4G_5$. The predicted lowest term ^{2}D (d^9) would give lines outside the present observed region and has not been found. The two $^4F'$, $^2F'$ terms belong to a sequence (d^8, s) and give a calculated I. P. of about 17.4 volts. The same peculiarities of convergence and interval are present in this $^4F'$, $^2F'$ series as were evident in the corresponding series of Cu II, Ni I and Pd I (d^9s).

63. Terms arising from similar and dissimilar electrons. D. T. Wilber, H. E. White and R. C. Gibbs, Cornell University.—Following the scheme of Hund for similar s, p and d electrons, the terms arising from similar f electrons have been worked out and tabulated. Tables have also been prepared for one and two electrons, where in the latter case these electrons are dissimilar, i. e., have either different total or different azimuthal quantum numbers, anu also for three electrons two of which are similar. In the tables for similar electrons we have indicated, in parenthesis, the total number of possible configurations of p (=number of possible values of m_a times the number of possible values of m_s) things taken q (=total number of electrons in consideration) at a time. These tables are found not only to be of frequent use but also to bring out certain rules that may be applied in determining spectral terms arising from any electron configuration.

64. Multiplets in the spectra of Cr(III) and Mn(III). R. C. Gibbs and H. E. White, Cornell University.—Following the method previously reported by us for the identification of multiplets in other isoelectronic systems of the first long period it has been found possible to extend the multiplet designated as $^5F-{}^5G$ for four electron systems (involving the transition $4p3d^3 \rightarrow 4s3d^3$) from Ti(I) and V(II) to Cr(III) and also the multiplet designated as ^{6}D$-{}^6F$ for five electron systems (involving the transition $4p3d^4 \rightarrow 4s3d^4$) from V(I) and Cr(II) to Mn(III). The twelve lines of the ^5FG multiplet of Cr(III) and the fourteen lines of the ^6DF multiplet of Mn(III) all follow the usual rule of relative intensities. These and other data enable us to extend further the systematic arrangement of radiated frequencies arising from the transition of an electron from a $4p$ to a $4s$ orbit in the presence of 0, 1, 2, 3 etc. $3d$ electrons, for elements in the first long period from K to Cu. The Moseley diagrams for the deepest lying terms arising from $d^{n-1}s$ and $d^{n-1}p$ configurations for these elements not only give very straight lines but also reveal a regular and systematic displacement in passing successively from one iso-electronic system to another.

65. The sodium and potassium absorption bands. W. R. Fredrickson, William W. Watson, and J. Rinker, University of Chicago.—The blue-green Na_2 and the red K_2 absorp-

tion bands have been photographed with a dispersion of 1.3A per mm. Vibrational quantum numbers have been assigned, with the following formulas giving the frequencies of the heads:

$$Na_2: \nu = 20301.62 + (123.84n' - 0.79n'^2) - (157.57n'' - 0.57n''^2)$$
$$K_2: \nu = 15368.63 + (74.46n' - 0.21n'^2) - (91.94n'' - 0.39n''^2)$$

Using Wood's resonance series data, the lines in the Na_2 bands are arranged into singlet P, Q, R branches, a result in accord with Mulliken's prediction of a $^1S - ^1P$ electronic transition. The resonance doublets have one component on the R, the other on the P branch, with $\Delta j = 2$; most of the singlets fall on Q branches. All of Wood's magnetic rotation lines lie on P and R branches. The usual P, Q, R combination principle holds. The band origins are very close to the heads; B_0' is 0.17 cm^{-1}. The K_2 bands appear to have four branches, indicating doublet P, R arrangement. If weak Q branches are present near the heads, they cannot be detected. The K_2 bands might involve a $^1P - ^1P$ transition (suggested by Mulliken) and it is shown that both ^1S and ^1P initial molecular states are plausible.

66. The rotational and vibrational specific heat of a diatomic gas, the molecules of which have a doublet P normal state. ENOS E. WITMER, National Research Fellow, Harvard University.—As is well known, the rotational and vibrational specific heat of a diatomic gas, the molecules of which have a single electronic state as the normal level, when plotted as a function of the temperature, shows the following characteristics. The curve rises more or less abruptly from zero at the absolute zero to a value in the neighborhood of R, after which the curve is almost flat until the vibrational energy begins to add its contribution. R is the gas constant in calories per degree (1.986). If, however, the normal electronic level is double, the specific heat curve presents in general in addition to this initial rise in the neighborhood of the absolute zero a secondary rise at the temperatures at which molecules begin to exist in the upper component of the doublet in appreciable numbers. After this second rise, which carries the curve above the value R, the curve again declines, tending to the value R, until vibration begins to add its contribution. A good example of the doublet type is nitric oxide. The specific heat of this gas was computed from the band spectrum data of Jenkins, Barton, and Mulliken. At 50°K. its specific heat is $1.33R$.

67. Recoil electrons from aluminum. A. A. BLESS, Cornell University.—On the Compton theory of scattering the maximum energy of the recoil electrons is given by $E = h\nu_0 2\alpha/(1+2\alpha)$. On the assumption made by C. T. R. Wilson that x-rays on scattering spread in spherical waves the maximum energy of recoil electrons would be about 1/4 that given above. Experiments on recoil electrons have been made with a molybdenum water cooled tube and aluminum as the scattering substance. Preliminary results using the magnetic spectrometer method show the presence of a band the high velocity edge of which agrees fairly well with the value predicted by Compton. The band shifted properly with the change of the field.

68. X-ray absorption formulas. S. J. M. ALLEN, University of Cincinnati.—Wetzel, using the new wave mechanics of Schroedinger, and applying it to photo-electric effect, has recently developed a formula for the absorption of high frequency x-rays for the K series. By the aid of Moseley's law the formula can be put in such form that it can be compared with experimental data. For a single element this formula is:

$$(\mu/\rho)_K = k_1\lambda^3 + k_2\lambda^{3.5} + k_3\lambda^{2.5} + \sigma/\rho$$

Using the same exponents of λ, empirical formulas can be found which agree, within experimental error, with existing data. The elements, Al, Fe, Cu, Ag, Sn, and Pb, have been considered from $\lambda = .081$ to $\lambda = 1.934$ A, and it has been found that such a formula fits the experimental data quite well through the entire range of λ for the K series. It also appears that such a formula fits the L series of Fe, Cu, and Pb, but that the L series of Ag and Sn, and the M series of Pb can be best expressed by two parameters. The complete formula for Ag is: $(\mu/\rho)\text{total} = (400\lambda^3 - 30\lambda^{3.5} + 80\lambda^{2.5})_K + (97\lambda^3 - 35\lambda^{3.5})_L + (1/6.5)(\tau/\rho_L)_M$ etc. $+ \sigma/\rho . \sigma/\rho = .35$ at $\lambda = .08$ A, and increases slowly with λ. From this formula, $J_k = (\tau/\rho_K + \tau/\rho_L + \tau/\rho_M$ etc.) $(\tau/\rho_L + \tau/\rho_M$ etc.) is not a constant but varies with λ.

69. Molecular space array in liquid primary normal alcohols: the cybotatic state. G. W. STEWART and ROGER M. MORROW, University of Iowa.—Examination of liquid normal primary alcohols, methyl to lauryl, by Mo Kα x-radiation, gives diffraction curves which are readily and consistently interpreted by the following: (a) There is a fluid molecular space array, called the "cybotatic" rather than "crystalline" state. (b) The alcohol molecules are parallel and separated by the most probable distance of 4.6 A. (c) The length of the molecules increases in equal amounts with each addition of CH_2; this increase is 1.3 A or approximately the distance between C atoms in crystalline form. (d) The above interpretations are in full accord with all known facts and especially to be noted is the agreement with the surface film molecular arrangement of similar compounds studied by Adam. The experiments and discussion refer to liquids that are optically isotropic. They are an extension of the work of numerous observers on the well known x-ray diffraction x-ray halo in liquids. The general conclusion is that *the cybotatic state or cybotaxis, is common in liquids and lends itself readily to a better understanding of the nature of a solution and solution phenomena, such as osmosis.*

70. X-rays of long wave-length from a ruled grating. F. L. HUNT, Bureau of Standards.—By the use of a grating ruled on glass (200 lines per mm), at grazing incidence (20′ to 40′), in vacuum, the following lines have been obtained: Mα of platinum, (6A); Kα of aluminum, (8.3A); Lα of copper, (13.3A), all in the first three orders; the Lα of iron, (17.7A) and of chromium, (21.5A), in the first order; and the Kα of carbon, (45A), in the first two orders. A water-cooled metal x-ray tube with a hot lime-coated platinum cathode, which permitted the use of an unprotected photographic plate, was connected directly to the spectrometer with no absorbing film between the anti-cathode and the plate. Two 0.5 mm steel slits 20 cm apart were mounted between the tube and the grating. The distance from the grating to the plate was from 10 to 30 cm. The voltage applied to the tube was 10 kilovolts, the current 10 milliamperes, and the time of exposure from 20 minutes to 1 hour. The wave-lengths were determined with reference to the first order Lα of copper which was used in computing the zero position of the direct beam. The angle of incidence on the grating and the effective distance from the grating to the photographic plate were determined experimentally. These preliminary measurements agree within approximately 0.1A with the values determined by reflection from crystals.

71. An explanation of Whiddington's rule for x-ray electrons. E. C. WATSON, California Institute of Technology.—In Whiddington's pioneer work on the velocities of electrons ejected by x-rays, the very remarkable observation was made that the incident radiation was able to eject an electron only when its frequency was double the value corresponding to the energy level of the electron concerned. Robinson, however, in his extensive study by the same method was unable to confirm this result. Robinson worked with electrons ejected approximately at right-angles to the x-ray beam, while Whiddington studied those leaving the radiator in the forward direction of the x-ray beam, and it can be shown that his rule resulted from this procedure together with the fact that x-ray plates become relatively insensitive to electrons whose HP velocity is less than 300. β-ray spectra have been taken at various angles with the x-ray beam, and lines which are forbidden by Whiddington's rule appear when the electrons leave the radiator approximately at right-angles to the x-ray beam but disappear when electrons leaving in the direction of the x-ray beam are studied. This is in agreement with the work reported at the Los Angeles Meeting (Abstract no. 24, March 5, 1927) and also with the work in gases by the expansion chamber method.

72. On a gyromagnetic electron-theory of the Compton effect. Louis VESSOT KING, McGill University.—In the following classical theory of the Compton effect, it is supposed that electrons are carried forward in a beam of monochromatic radiation of high frequency. The equations of motion of the electron, taking into account the variation of mass with velocity, may be solved by successive approximation. The electron describes a trajectory of sinusoidal form whose period differs slightly from that of the incident radiation, while the resultant velocity depends on the magnitude of the electric intensity in the electromagnetic wave. The dis-

turbing couples on the gyromagnetic electrons are provided by couples arising from the corresponding magnetic field. On inserting these conditions in the gyromagnetic equations of line radiation (*Gyromagnetic Electrons and a Classical Theory of Radiation and Atomic Structure*, Louis Carrier, Mercury Press, Montreal), it is found that a certain group of electrons (whose velocities give rise to a natural precessional frequency synchronizing with that of the disturbing couple) will precess by resonance, emitting line radiation of frequency differing slightly from that of the incident beam. Since the precessing electron moves forward while radiating, the application of the classical Doppler principle gives the well-known complete formula for the Compton effect.

73. Iron crystals. L. W. McKeehan, Bell Telephone Laboratories, Inc.—It has been found possible to grow long crystals in iron wire by making use of the allotropic transformation which occurs at about 900°C. The method is to heat, in an inert atmosphere, a portion of the wire between two mercury contacts by passing direct or alternating current through it and then to cause the heated portion to travel along the wire either by moving the support carrying the contacts or by moving the wire itself. The hottest part of the wire should be at 1400°C or higher. Under these conditions a very steep temperature gradient exists at the point where face-centered cubic (γ) crystals, stable at high temperatures, are being replaced by body-centered cubic (α) crystals, stable at lower temperatures, and at a favorable velocity of travel a single α crystal will grow to a length of 20 centimeters or more in wire 1 millimeter in diameter. The chemical purity and previous mechanical history of the iron seem relatively unimportant. Irregularity in tension on the wire and torsional stresses in it result in twinning Twins may either appear as small inclusions or as complete changes in orientation with the twinning plane traversing the entire cross-section of the wire. The twinning plane is of the form $\{211\}$. The magnetic and magnetostrictive properties of the long crystals appear in some respects to differ from those of crystals prepared by others by the method of over-strain and annealing.

74. The purification of helium. J. Williamson Cook, Bureau of Standards.—Helium containing 2.91 percent air (mostly nitrogen) plus a trace of hydrogen and neon, was passed at a slow rate and at atmospheric pressure, over activated cocoanut charcoal which had been thoroughly outgassed at from 300° to 400°C. With the charcoal cooled to −78°C. all air was adsorbed by the charcoal, leaving helium with only a trace of neon and hydrogen when observed spectroscopically. The charcoal was 100 percent efficient for removing air until its saturation limit was approached, when its efficiency failed almost instantly and completely. At lower temperatures, considerably more air was adsorbed but the saturation limit was not quite so abrupt. The amount of air, in cubic centimeters, which was adsorbed per gram of charcoal, up to the saturation limit, was 7 cc at −78°C; 152 cc at −182°C; 217 cc at −209°C. Relative observations, at liquid air temperature, indicated that if the hydrogen was first removed chemically, the charcoal would then adsorb more neon than when the hydrogen and neon were both present in the helium.

75. Duration of atomic hydrogen. Joseph Kaplan, Johns Hopkins University. (Introduced by R. W. Wood.—A large bulb of 3 liters capacity was sealed to the middle of a Wood's hydrogen tube and the atomic hydrogen formed in the discharge tube was allowed to enter the bulb. It was found that atomic hydrogen could be detected, by means of a speck of Welsbach mantle, three seconds after the discharge was shut off. The piece of Welsbach was quite large which indicated that there was still probably considerable atomic hydrogen in the bulb even after three seconds. Certain other effects, such as small white infected spots on the glass, which were due to atomic hydrogen, were observed for as long as six seconds after the discharge was discontinued. There were indications that the atomic hydrogen lasted as long as 10 seconds, but, because of impurities in the tube, these indications may have been due to something else. It has also been shown that in the absence of water, a surface is a much better catalyzer than when water is adsorbed on it. The present experimental proof of the role of water has, however, been made away from the discharge tube, in which other complicated reactions might occur.

76. Structure and isotope effect in the alpha bands of boron monoxide. F. A. JENKINS National Research Fellow, Harvard University.—The α bands of BO excited by active nitrogen have been photographed with high dispersion. They are electronic doublets, each component having four branches designated R_1, (R_2+Q_1), (Q_2+P_1), and P_2, of which the two central ones are relatively more intense. This structure has been interpreted by Mulliken as due to a $^2P\rightarrow{}^2S$ transition. The missing lines support this designation, since there is one in the Q_1–Q_2 series for the higher frequency system, while there are three for the lower. The ^2P doublet is therefore *inverted*. Quantum analysis of the $(\frac{1}{2}, \frac{1}{2})$ and $(\frac{1}{2}, 1\frac{1}{2})$ higher frequency sub-bands shows that the rotational terms in the initial state are of the form $B'(j^2-\sigma^2)$, $\sigma=\frac{1}{2}$, and in the final state $B''(j-\epsilon)^2$, $\epsilon=\pm\frac{1}{2}$, with j integral. There is a close σ-type doubling in the initial state, but "crossing over" in the Q transitions allows the coalescence of R_2 with Q_1, and Q_2 with P_1. The origins of the $(\frac{1}{2}, \frac{1}{2})$ bands of $B^{10}O$ and $B^{11}O$ are separated by 1.547 A, exactly the amount required for half-integral vibrational quantum numbers. Analysis of this $B^{10}O$ band gives smaller moments of inertia than those obtained for $B^{11}O$, but identical internuclear distances, namely $r_0'=1.352\times10^{-8}$ cm and $r_0''=1.208\times10^{-8}$ cm.

77. Band structure and intensities, atomic and molecular electronic states, in diatomic hydrides. ROBERT S. MULLIKEN, New York University, Washington Square College.—Theoretical intensity formulas applicable to $^2P\rightarrow{}^2S$ and $^2S\rightarrow{}^2P$ molecular electronic transitions have been obtained, for Hund's case b. The observed branches (six intense branches), intensity relations, missing lines, etc., in the CaH, MgH ($^2P\rightarrow{}^2S$), OH, CH λ3900 ($^2S\rightarrow{}^2P$) bands agree well with the theory. As the ^2P separation increases, through ZnH, CdH, to Hg^1H (all $^2P\rightarrow{}^2S$), and the ^2P state approaches Hund's case a, a gradual transition occurs to the HgH type, with twelve strong branches. In OH (as expected), apparently also in CH, the ^2P doublet is inverted; elsewhere it is normal. The intensity relations, probable missing lines, and occurrence of twelve strong branches (different from those in HgH), show that CH λ4300 is $^2D\rightarrow{}^2P$. Probably the three levels ^2P, ^2D, ^2S involved in CH $\lambda\lambda$ 4300 and 3900 are derived, by the addition of a normal hydrogen atom, from the lowest levels, ^3P, ^1D, ^1S of the carbon atom (the latter two metastable, unlike ^2D and ^2S of CH); the OH levels ^2P and ^2S similarly from ^3P and ^1S of oxygen; and the ^2P and ^2S levels of the metal hydrides from the lowest levels (^1S, ^3P) of the metal atoms.

78. Zeeman effect in AgH, AlH, ZnH, and MgH bands. WILLIAM W. WATSON and B. PERKINS JR., University of Chicago.—The AgH bands are absolutely unaffected by magnetic fields of any strength, thus verifying the assignment $^1S-{}^1S$ to these bands. The results for the λ4240 AlH band ($^1S-{}^1P$) are similar to those given by Kemble and Mulliken for the λ5610 CO band ($^1P-{}^1S$). The first R lines are broadened, the spread of the R(1) components being approximately half normal separation, in agreement with Van Vleck's "rigid-coupling" formula, if $j'=1$. The first P and Q lines are diffusely broadened. In the λ4326 ZnH band results at medium field strength are in agreement with Hulthen's except for the R_1 lines. These show a broadening for low $m's$, as do the R_2 lines. The P_1 and P_2 lines are unaffected at any field strength. Both the Q_1 and Q_2 lines split up into "loose-coupling" wide doublets ($\Delta\nu=2\times$normal separation for low $m's$.) A first order "rigid-coupling" effect on the Q lines at low fields apparently occurs, but measurements are uncertain. In the MgH bands the narrow doublets fuse into single lines more intense in the center and slightly narrower than the original doublets.

79. The excitation of the spectrum of CO_2. G. W. FOX, O. S. DUFFENDACK and E. F. BARKER, University of Michigan.—Pure CO_2 flowing continuously through a hot cathode discharge tube was excited by electron impacts at low voltages. The tube consists of two compartments separated by a diaphragm having a small aperture covered with platinum gauze through which the electrons from an oxide coated filament enter the impact chamber. The flow of gas was in the direction opposite to that of the electrons; thus dissociation products were swept out through the pump and no diffusion into the region of observation occurred. The gas pressure was controlled by regulating the rate of flow. Under these conditions the spectrum observed

is altogether different from that produced in stagnant gas, and is attributed to the molecule of CO_2. The glow is violet and its spectrum consists of several systems of bands extending from 5000 A to 2850 A. Most of these bands are degraded toward the red. They have sharp edges, and occur in distinct groups. One group lying near 2880 A seems unique. It consists of two double edged bands each having oppositely degraded branches with a very narrow band between their edges. When the flow is stopped the familiar sky blue of CO appears at once, and the spectrum consists mainly of the positive bands of CO.

80. Ultra-violet absorption and emission spectra of carbon monoxide. J. J. HOPFIELD and R. T. BIRGE, University of California.—New emission and absorption spectrograms of CO have been measured and analyzed. Many irregularities in some previous data by others have been eliminated. By gradually varying the pressure of CO in the receiver of the spectrograph from 0.05 to 850 mm, nine absorption systems, between λ920 and λ2064.5 have been obtained. These represent transitions from the normal level to *all* of the previously known excited electronic levels (Phys. Rev., **28**, 1157 (1926)) and to four new levels at 58927, 92923,* 99730, and 105270 cm^{-1}. Other absorption systems are present but are too blended for certain analysis. The new data permit many satisfactory tests of the combination principle, and give as a direct evaluation of the previously known levels, 48438* to 48534,* 64765,* 83812* (poor) 86926,* and 91923* cm^{-1}. Band systems are found in emission also, for transitions from starred levels directly to the normal. The strongest absorption is to the highest levels. Three of the higher levels have a vibration frequency almost identical with that of the normal state, and this fact, coupled with the absence of a Q branch in the correlated bands, predicts unique features in the appearance of the bands which are experimentally verified.

81. A comprehensive form of energy level diagram for atoms. RAYMOND T. BIRGE, University of California.—A type of diagram is suggested which may include, at least theoretically, all energy levels of an atom and its singly, doubly, etc. charged ion, provided that not more than one electron is in an excited level. A general scheme is proposed for designating the levels in accordance with the present interpretation of complex spectra. Such a diagram exhibits all possible relations between the lines of ordinary spectral series, the enhanced series of the variously charged ion, the ordinary x-ray lines, the enhanced (spark) x-ray lines, the critical absorption limits, and the so-called discontinuities in the absorption limits. With emission represented as a downward transition, the x-ray energy levels appear inverted with the K level highest. All levels for the neutral atom are represented by parallel sets of vertical columns, grouped in one section. Similarly all levels of the singly charged atom, in an adjoining section. Transitions representing monochromatic radiation never cross the division between sections. All critical absorption limits do cross. Double electron jumps are not represented, as the number of types of possible levels, with more than one electron in an excited state, in prohibitively great for convenient representation.

82. The shift in a near infra-red absorption band of some benzene derivatives. JAMES BARNES, Bryn Mawr College.—By means of a grating spectroscope and plates sensitized with neocyanine absorption bands of benzene and of some of its derivatives have been photographed and their wave-lengths measured. The dispersion of the spectrometer as used was approximately 39.8 A to the millimeter. The results are believed to be accurate to ±5 A. The wave-lengths of the center of the absorption bands of the substances used are as follows:

	λ(A)		λ(A)
Benzene	8741	M-Xylene	8793
Toluene	8758	P-Xylene	8808
Ethylbenzene	8772	Diethylbenzene	8799
O-Xylene	8781	Mesitylene	8844

With an absorption cell 80 cms in length benzene shows an absorption band at 7134 A. Some interesting conclusions can be drawn from these results. Their explanation in the light of present theories regarding band spectra will be briefly discussed.

83. The infra-red absorption spectra of acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6). CHARLES F. MEYER and AARON LEVIN, University of Michigan.—The absorption spectra of the above gases are being investigated by means of a grating spectrometer. The curves show fine structure of an interesting and, in some cases, an extremely regular nature. They are the first which show resolution of bands into ultimate lines for molecules containing more than one heavy atom. That is, all bands of the vibrational-rotational type which have hitherto been analyzed, originate from molecules which contain hydrogen and only one atom of another kind. Investigators have felt that the bands of other molecules, on account of the higher moment of inertia involved, and consequent closer spacing of the lines, were unresolvable. This is shown to be untrue for the gases under investigation. The measurements extend to nearly 15μ and have thus been carried to considerably longer wave-lengths than any previous work with high dispersion.

84. The infra-red spectrum of ammonia. W. F. COLBY and E. F. BARKER, University of Michigan.—The absorption band for ammonia at 10μ has been observed with high dispersion, and analyzed as two overlapping bands with zero branches at 10.3μ and 10.7μ. Each band has the same general structure. About twelve lines have been observed in each branch, the spacing being somewhat different in the two bands, about 18.9 cm^{-1} for one and 20.4 cm^{-1} for the other. There is very little convergence. It is suggested that these two bands result from the two transitions $1/2 \rightarrow 3/2, 3/2 \rightarrow 5/2$ (or perhaps $1/2 \rightarrow 5/2, 3/2 \rightarrow 7/2$) for the same normal vibration of the molecule. The slight change in line spacing is due to coupling. Other ammonia bands previously reported are interpreted in terms of two different types of transition, one in which the second rotational quantum number changes (1.9μ and 2.2μ) and the other where it does not change (6μ and harmonics). The band at 10μ belongs to the latter class. Possible values of the two moments of inertia for the symmetrical pyramid NH_3 are obtained.

85. The infra-red reflection spectra of some carbonates. E. K. PLYLER, University of North Carolina.—A rock salt prism was used to examine the spectra of some carbonates. As the source of radiation a material called Globar was used. It was found to be about four times as intense as a Nernst glower in the region of 7μ. The structure of the band of selective reflection of calcium carbonate was studied by reflecting the radiation from the surface of a clear piece of calcite. The slit width was .07 mm. Maxima were found at 6.36μ 6.54μ, and 6.62μ. These different maxima are probably due to the isotopes of calcium. If the three maxima are caused by the isotopic effect, then calcium should have three isotopes rather than two. The reflection spectra for iron carbonate had two maxima. Dolomite also had two maxima.

86. Intensity relations and band structure in bands of the violet CN type. ROBERT S. MULLIKEN, New York University, Washington Square College.—Theoretical intensity formulas applicable to bands of the violet CN ($^2S \rightarrow {}^2S$) type are obtained, assuming Hund's case *b*. These predict two *Q* branches (*RQ* and *PQ*) which should appear as weak satellite series, one accompanying the familiar double *P* branch, the other, the *R* branch. These *Q* branches should decrease in intensity from their first members. The first *RQ* (or *PQ*) line should accompany the otherwise single first line of the *R* (or *P*) branch (all other *P* and *R* lines are truly double); this result is in agreement with Hulthén's results on the CaH "*B*" bands. In the *P* (and *R*) branches, the doublet component corresponding to the parallel orientation ($+\epsilon$) of the electron spin vector should be appreciably more intense than that corresponding to the antiparallel orientation ($-\epsilon$) for low *j* values. Treating the doublets (and their satellites) as unresolved single lines, the intensities should be exactly as in $^1S \rightarrow {}^1S$ bands (CuH, HCl). These predictions seem to be confirmed in the CaH, N_2^+, and violet CN bands. Thus the theory appears to afford a satisfactory explanation of the observed lines and intensity relations in $^2S \rightarrow {}^2S$ bands, removing previous difficulties and uncertainties in interpretation.

87. Some unclassified lines of oxygen in the ultraviolet. J. J. HOPFIELD, University of California.—Some of the ultraviolet lines of the arc spectrum of oxygen not yet fitted into series are λ1152 and a triplet λλ988.67, 990.13, and 990.73. These are among the strongest

lines and no doubt belong to OI. The triplet is perhaps an unresolved group similar to one in sulphur at λ1480 (unpublished work) which contains eight lines, the normal triplet separation occurring twice. The discrepancy of the separations of the above triplet of oxygen from the normal separation may be explained on this basis. λ1152 is always accompanied by a diffuse band or group on its ultraviolet side. Two single lines λλ1217.62 and 999.47, the latter measured with the carbon line λ1037.021 as standard, occur in the arc spectrum of oxygen with relative intensities of 5 and 7 respectively, the separation of these lines being 17925.6 cm^{-1}. The green aurora line attributed to oxygen has a frequency 17924.7 cm^{-1}. The difference between these two values is 0.9 cm^{-1}, so that the two numbers are identical to within limits of experimental error. This tends to indicate that this aurora line λ5577.35 I. A. is related to the two ultraviolet lines of oxygen, the most plausible relation being that the ultraviolet lines have a common initial or final state and the aurora line represents the transition between their respective final or initial states.

88. X-ray absorption and valence. W. B. MOREHOUSE, Westinghouse Lamp Company.—Experiments reported at the Washington Meetings, April, 1926, suggested that the absorption of heterogeneous x-rays by an element depends upon its valence. Results obtained from the same reactions using zirconium filtered beams indicate the same general results, but the magnitude appears to be somewhat greater, which suggests that the effect may be different for different wave-lengths. From a combination of Moseley's Law with the absorption law it can be shown that at the absorption limit, $d\tau_a/\tau_a = 6db/(N-b)$ where τ_a = atomic absorption coefficient at the short wave-length side of the K limit, b = screening constant, and N = atomic number which indicates that if the screening constant changes the absorption coefficient will change. Existing data shows that the emission and absorption spectra depend upon the valence; in general the higher the valence the shorter the wave-length, which from Moseley's law indicates that the screening constant decreases, which in turn indicates qualitatively that the absorption coefficient should decrease with increase in valence. Calculations from the difference in wave-length of the L limits for iodine in the free state and iodine in sodium iodide gives a decrease in absorption of approximately 0.4 percent which is in agreement with experimental results. Hence with change of valence there must be a slight change in the electron configuration of the atom. (This work was done at Cornell University.)

89. Report on the ether-drift experiments at Cleveland in 1927. DAYTON C. MILLER, Case School of Applied Science.—The ether-drift interferometer which was used at Mount Wilson in California in the experiments of 1921–1926 has been mounted on the campus at Case School of Applied Science in Cleveland. Only minor changes, suggested by experience, have been made in the apparatus. Special precautions have been taken to obviate troubles caused by vibration from city traffic. A series of observations which will extend throughout the year, comparable with those made at Mount Wilson, is now in progress. The results for the first epoch of the series indicates an effect of the same order of magnitude as was obtained at Mount Wilson and consistent with the conclusions previously announced.

90. The photo-electromotive force in selenium. R. L. HANSON, Cornell University. (Introduced by F. K. Richtmyer.)—A detailed study was made of the e.m.f. developed in a selenium cell by illumination, an effect originally discovered by Adams and Day in 1876 and later observed by Fritts, Uljanin and others. Careful investigation has shown this not to be a thermal e.m.f. The results of the investigation up to date are the following: (1) For the same illumination the e.m.f. is independent of the current through the cell. (2) Over wide ranges the e.m.f. is directly proportional to the intensity of illumination. (3) For the same intensity of illumination the e.m.f. is a maximum in the region $\lambda = 490$.

91. Charge Density in the new mechanics. R. M. LANGER, Naval Research Laboratory, Washington, D. C. (Introduced by G. Breit.)—The Schrödinger expression for the electric moment can be written $\mu^2 - 1 = N_1/(\nu_1^2 - \nu^2) + N_2/(\nu_2^2 - \nu^2) + N_3/(\nu_3^2 - \nu^2) + \cdots$. This is the form of the classical dispersion formula in which the N_i's indicate the number of oscillators capable of emitting the frequencies ν_i. For the case of the hydrogen atom the first terms have

the numerical values 1.52, 0.28, 0.06 and the sum of the series gives a value for the refractive index which is larger than that found experimentally (Proc. Nat. Acad. **12,** 639 (1926)). But if we say that in the expression of $\psi\bar{\psi}$ for atoms originally in the state k acted on by a light wave, the terms of the form $C_{nk}u_nu_k$ can be taken quite literally as indicating the presence of charge distributions described as to extension by u_n u_k and as to concentration by C_{nk}, and if we say that these just as other ordinary atoms, electrons or molecules are subject to collisions in the kinetic theory sense, then we find since the higher states u_nu_k occupy such large volumes that at the pressures of the experiments (about 1 mm) they collide so often that their contribution to the coherent scattering and therefore to the refractive index is greatly diminished. So far from being a difficulty, what was apparently a discrepancy between theory and experiment becomes on this point of view, evidence in favor of what some may regard as a rather extreme form of the theory.

92. A method for determining sound transmission. F. R. WATSON, University of Illinois.—A sound generated in an electric loud speaker by means of an electron tube oscillating circuit is situated on one side of a test wall, or inside a "sound-proof" room. On the other side of the partition is an observer who listens to the transmitted sound. A comparison sound is set up by a microphone placed a fixed small distance in front of the loud speaker, which transmits an electric current through a transformer and variable resistance to a pair of head telephones worn by the observer. The resistance is varied until the telephone tone just masks the sound transmitted through the partition. This measurement is repeated when the observer stands near the loud speaker, which is reckoned as 100 percent. The ratio of the measurements of the transmitted sound to the direct (100 percent) sound gives the percentage of sound transmitted. Preliminary measurements of sound proof rooms gave satisfactory results.

93. Excitation of CuII spectrum by positive neon ions. O. S. DUFFENDACK AND J. G. BLACK, University of Michigan.—The method of Duffendack and Smith of employing positive ions to excite the spectrum of a once-ionized molecule with the exclusion of higher spark spectra was applied to copper. Low-voltage arcs of 20 milliamperes at 25 volts were maintained in mixtures of argon and copper and neon and copper in a tungsten furnace apparatus and their spectra photographed with a Hilger E2 quartz spectrograph. The pressure of the copper vapor was regulated by controlling the temperature of the furnace so that the green arc lines were faintly visible in a direct vision spectroscope. Under these conditions, the argon mixture failed to produce any spark lines. In neon the lines from the levels corresponding to the $(3d)^9$ $(4p)$ and $(3d)^9$ $(5s)$ configurations were strongly developed. These results are in accord with Shenstone's (Phys. Rev. **29,** 380, (1927)) analysis of the spark spectrum as the $(3d)^9$ $(4p)$ levels lie at 15.9 to 16.8 volts and the $(3d)^9(5s)$ at 21.0 to 21.4 volts above the normal state of the coppper atom. Thus argon ions (15.4 volts) just fail to produce the lower state and neon ions (21.5 volts) can just produce both. In the neon mixture the lines from the higher level were considerably more intense relative to those from the lower level than they are in the ordinary spark.

94. The Stark effect in neon. J. S. FOSTER AND W. ROWLES, McGill University.—By employing a rather strong Lo Surdo source in which a maximum field of 130,000 v/cm was developed, the earlier observations by Nyquist have been somewhat extended. The observed symmetrical Stark patterns for the line groups of higher order (notably $2p_i-6q$ and $2p_i-7q$) are *remarkably hydrogen-like* in character. In these groups the complex nature of the initial states is not detected by the Hilger E1 spectrograph. On the other hand, each of the lines $2p_i-4f$ and $2p_i-5f$ appears as a doublet and the two members of the doublet present Stark-effects which are nearly identical. This effect is similar to that noted in orthohelium, where the multiplicity is in the final state. The initial terms involved in the production of the group of new lines which commonly appear in the electric field are more hydrogen-like than the diffuse terms, and consequently the majority of these lines have exceptionally large displacements. On the present plates some are displaced more than 50A. Another large group of new lines appear, however, without appreciable displacements, but with intensities which increase rapidly with the field. These ionized neon lines simply indicate the proportion of Ne^+ atoms in the various fields.

AUTHOR INDEX

Allen, S. J. M.—No. 68

Barker, E. F.—see Colby
———see Fox
Barnes, James—No. 82
Beams, J. W. and Ernest O. Lawrence—No. 9
Beams, J. W.—see Lawrence
Bennett, Arthur Lowell—No. 40
Birge, Raymond T.—No. 81
Birge, Raymond T.—see Hopfield
Black, J. G.—see Duffendack
Bless, A. A.—No. 67
Bourgin, D. G.—No. 45
Brasefield, Charles J.—No. 57
Brickwedde, F. G. and W. A. MacNair—No. 59

Campbell, G. C. and G. W. Willard—No. 46
Castleman, R. A., Jr.—No. 34
Colby, W. F. and E. F. Barker—No. 84
Compton, K. T. and P. M. Morse—No. 31
Compton, K. T.—see Van Voorhis
Cook, J. Williamson—No. 74

Davis, Raymond and K. S. Gibson—No. 60
Davisson, C. and L. H. Germer—No. 27
Dennison, D.—see Dushman
Duffendack, O. S. and J. G. Black—No. 93
Duffendack, O. S. and H. L. Smith—No. 53
Duffendack, O. S.—see Fox
Dushman, S., D. Dennison and N. B. Reynolds—No. 7

Ellett, A.—No. 11
Ewell, Arthur W.—No. 43

Farnsworth, H. E.—No. 30
Foster, J. Stuart—No. 58
Foster, J. Stuart and W. Rowles—No. 94
Fowle, E. S.—see Pienkowsky
Fox, G. W., O. S. Duffendack and E. F. Barker—No. 79
Frederickson, W. R., William W. Watson, and J. Rinker—No. 65

Galli-Shohat, N.—No. 20
Germer, L. H.—see Davisson
Gibbs, R. C. and H. E. White—No. 64
Gibbs, R. C.—see Wilber
Gibson, K. S.—see Davis
Gish, O. H.—see Rooney

Ham, W. R.—No. 29
Hamer, Richard and Surain Singh—No. 2
Hanson, R. L.—No. 90
Harnwell, Gaylord P.—No. 22
Hartsough, R. C.—No. 35
Heyl, Paul R.—No. 36
Hidnert, Peter and W. T. Sweeney—No. 39
Hopfield, J. J.—No. 87
Hopfield, J. J. and R. T. Birge—No. 80
Hughes, A. L. and A. M. Skellett—No. 25
Hunt, F. L.—No. 70

Jenkins, F. A.—No. 76

Kaplan, Joseph—No. 75
Karapetoff, Vladimir—No. 51
Kenty, Carl and Louis A. Turner—No. 52
King, Louis Vessot—No. 72
Kinsey, E. L.—see Wood
Kleeman, R. D.—No. 44
Koller, L. R.—No. 6
Krefft, Hermann E.—No. 28
Kunz, Jacob—No. 37
Kunz, Jacob—see Tykocinski-Tykociner
Langer, R. M.—No. 91
Lawrence, Ernest O. and J. W. Beams—No. 10
Lawrence, Ernest O.—see Beams
Levin, Aaron—see Meyer
Libman, E. E.—No. 41
Little, Noel C.—No. 1

MacMahon, A. M.—No. 3
MacNair, Walter A.—No. 56
MacNair, Walter A.—see Brickwedde
McCurdy, W. H.—No. 55
McKeehan, L. W.—No. 73
Martin, John R.—No. 19
Meyer, Charles F. and Aaron Levin—No. 83
Miller, Dayton C.—No. 89
Morehouse, W. B.—No. 88
Morrow, Roger M.—see Stewart
Morse, P. M.—see Compton
Mulliken, Robert S.—Nos. 77 and 86
Murhaghan, Francis D. and Harold A. Wheeler—No. 50

Nielsen, Walter M.—No. 23
Nusbaum, C.—No. 16

Parmley, T. J.—No. 5
Phipps, T. E.—see Taylor
Pienkowsky, A. T. and E. S. Fowle—No. 38
Piersol, R. J.—No. 4
Plyler, E. K.—No. 85
Pool, M. L.—No. 54

Race, Hubert H.—No. 48
Reynolds, N. B.—see Dushman
Rinker, J.—see Frederickson
Rooney, W. J. and O. H. Gish—No. 17
Rowles, W.—see Foster
Rusk, Rogers D.—No. 24

Sagui, Cornelio L.—No. 21
Shenstone, A. G.—No. 62
Singh, Surain—see Hamer
Skellett, A. M.—see Hughes

Smith, H. L.—see Duffendack
Solt, Irvin H.—No. 12
Spencer, R. C.—No. 33
Stewart, G. W. and Roger M. Morrow—No. 69
Swann, W. F. G.—No. 15
Sweeney, W. T.—see Hidnert

Taylor, John B. and T. E. Phipps—No. 13
Tonks, Lewi—No. 47
Turner, Louis A.—see Kenty
Tykocinski-Tykociner, J. and J. Kunz—No. 14

Van Voorhis, C. C. and K. T. Compton—No. 32

Warburton, F. W.—No. 18
Watson, E. C.—No. 71
Watson, F. R.—No. 92
Watson, William W. and B. Perkins, Jr.—No. 78
Watson, William W.—see Frederickson
Wheeler, Harold A.—No. 8
Wheeler, Harold A.—see Murnaghan
White, H. E.—see Gibbs
White. H. E.—see Wilber
Wilber, D. T., H. E. White and R. C. Gibbs—No. 63
Willard, G. W.—see Campbell
Winchester, George—No. 42
Witmer, Enos E.—No. 66
Worthing, A. G.—No. 26
Wood, R. W. and E. L. Kinsey—No. 61

Zimmermann, E. E.—No. 49

AUTHOR INDEX TO VOLUME 29

References with (A) are merely to abstracts of papers presented at meetings of the Physical Society.

Alexeievsky, A. P. Some remarks on the formation of negative ions—752(A)

Allen, S. J. M. X-ray absorption formulas—918(A)

Allis, W. P. and Hans Mueller. Wave theory of the electron—361(A)

Allison, Fred. Effect of wave-length on the differences in the lags of the Faraday effect behind the magnetic field for various liquids—370(A)

——— (see Beams, J. W.)—161

Allison, Samuel K. Reflection of x-rays by crystals as a problem in the reflection of radiation by parallel planes—375, 748(A)

Anderson, S. H. Striking potentials of metallic arcs in vacuo—750(A)

——— (see Ostenson, Floyd C.)—753(A)

Babcock, Harold D. Study of the infra-red solar spectrum with the interferometer—748(A)

Barker, E. F. (see Colby, W. F.)—923(A)

——— (see Fox, G. W.)—921(A)

——— (see Stinchcomb, G. A.)—213(A)

Barnes, James. The shift in a near infra-red absorption band of some benzene derivatives—922(A)

Barrett, C. S. and **J. A. Bearden.** The polarizing angle for x-rays—352(A)

Barton, Henry A. Ionization in HCl vapor—608(A)

——— (see Jenkins, Francis A.)—211(A)

Bateman, H. Motion of an airship in a variable horizontal wind—755(A)

Baudisch, O. (see Welo, L. A.)—612(A)

Bauer, Louis A. Cosmic aspects of atmospheric electricity—371(A)

Baxter, Warren P. (see Dalton, Robert H.)—248

Bayley, P. L. X-ray coloration of kunzite and hiddenite—353(A)

Beams, J. W. and **Fred Allison.** Differences in the time lags of the Faraday effect behind the magnetic field in various liquids—161

Beams, J. W. and **Ernest O. Lawrence.** New method of determining the time of appearance and time of duration of spectrum lines in spark discharges—357(A)

——— Study of the lag of the Kerr effect for several liquids as a function of the wave-length of the light—903(A)

Beams, J. W. (see Lawrence, Ernest O.)—903(A)

Bearden, J. A. Measurement and interpretation of the intensity of x-rays reflected from sodium chloride and aluminum—20

——— (see Barrett, C. S.)—352(A)

Becker, J. A. Life history of an adsorbed atom of Cs—364(A)

Begeman, Hilda (see McDowell, Louise S.)—367(A)

Bennett, Arthur Lowell. Resolving power of the ears—911(A)

Bennett, R. D. Some properties of Geiger counters—363(A)

Birge, R. T. Comprehensive form of energy level diagram for atoms—922(A)

——— and **A. Christy.** The titanium bands—212(A)

——— and **J. J. Hopfield.** Ultra-violet band spectra of nitrogen—356(A)

——— (see Hopfield, J. J.)—922(A)

Black, J. G. (see Duffendack, O. S.)—358(A), 925(A)

Blake, F. C., James Lord and **A. E. Focke.** Solid solutions of chromium and nickel and of iron and nickel—206(A)

Bless, A. A. Recoil electrons from aluminum—918(A)

Bobrovnikoff, N. T. The spectra of comets—210(A)

Boord, Cecil E. (see Smith, Alpheus W.)—355(A)

Bourgin, David G. Molecular fields—368(A)

——— Line intensities in the HCl fundamental band—794

——— Vacuum tube oscillator—912(A)

Bowen, I. S. Series spectra of B, C, N, O and F—231

——— Series spectra of ionized phosphorus, P_{II}—510, 749(A)

——— (see Millikan, R. A.)—749(A)

Bozorth, Richard M. and F. E. Haworth. Crystal structure of magnesium platinocyanide heptahydrate—233

Brasefield, Charles J. H_3 as a possible emitter of the secondary hydrogen spectrum—915(A)

Breit, G. Suggestion of an explanation of the long life of metastable atoms—361(A)

——— Book Reviews—200, 348, 601

Brewer A. Keith. Factors influencing thermionic emission—752(A)

Brickwedde, F. G. and **W. A. MacNair.** Light absorption of liquified gases—916(A)

Bridgman, P. W. Breakdown of atoms at high pressures—188
——— Book Reviews—201, 202, 349, 897
Brown, S. L. and **M. Y. Colby.** Electrical measurements at radio frequencies—717
Brown, S. L., C. F. Wiebusch and **M. Y. Colby.** High frequency resistance of a Bureau of Standards type variable air condenser—887
Bush, V. and **King E. Gould.** Temperature distribution along a filament—337
Butts, Donald C. A., Thomas E. Huff and **Frederick Palmer, Jr.** A preliminary report on the study of the emission spectra and surface tension alterations in experimental animal tumors—219(A)

Cady, W. G. Shear mode of crystal vibration—617(A)
——— Book Reviews—199, 896
Cajori, Florian. Book Reviews—197, 346, 492
Campbell, G. C. and **G. W. Willard.** Device to draw characteristic curves of vacuum tubes automatically—913(A)
Carman, A. P. and **K. H. Hubbard.** Determination of the dielectric constant of air by a discharge method—217(A), 299
Castleman, R. A., Jr. Log, semi-log, and uniform coordinator—910(A)
Cheney, E. W. Measurement of index of refraction of gases at higher temperatures—292
Christy, A. (see Birge, R. T.)—212(A)
Clarke, Harry. Measurement of x-rays used for therapy—605(A)
Coblentz, W. W. Tests of a new selective radiometer of molybdenite—615(A)
——— and **C. W. Hughes.** New selective radiometer of molybdenite—365(A)
——— and **C. O. Lampland.** Radiometric measurements on the planet, Mars, 1926—372(A)
Colby, M. Y. (see Brown, S. L.)—717, 887
Colby, W. F. and **E. F. Barker.** Infra-red spectrum of NH_3—923(A)
Compton, K. T. and **P. M. Morse.** Theory of the normal cathode fall—909(A)
Compton, K. T. (see Van Voorhis, C. C.)—909(A)
Constantinides, Philip A. Electrical properties and nature of active nitrogen—215(A)
Cook, J. Williamson. Purification of helium—920(A)
Cravath, A. M. (see Jones, L. T.)—871
Crew, W. H. and **E. O. Hulburt.** Pressures in discharge tubes, Part I, Long slim tubes—609(A)
——— Number of radiating atoms in a hydrogen discharge tube—843

Dalton, Robert H. and **Warren P. Baxter.** Velocity distribution of electrons issuing from small holes—248
Darrow, Karl K. Book Reviews—493, 898
Davey, Wheeler P. Theory of the mechanism of crystal growth—206(A)
——— Book Review—492
Davis, Raymond and **K. S. Gibson.** Reproducible liquid filters for the determination of the color temperature of incandescent lamps—916(A)
Davisson, C. and **L. H. Germer.** Scattering of electrons by a nickel crystal—908(A)
Dawson, L. H. Movements of striae in discharge tubes under varying pressures—610(A)
——— Piezo-electricity of crystal quartz—216(A), 532
Del Rosario, C. Low pressure electric discharge in intense electric fields—360(A)
Dennison, D. (see Dushman, S.)—903(A)
Dickenson, R. G. (see Mitchell, A. C. G.)—751(A)
Doan, Richard L. Refraction of x-rays by method of total reflection—205(A)
Duane, William. General radiation from a very thin target—606(A)
DuBridge, Lee A. Photoelectric properties of thoroughly outgassed Pt—451
Duffendack, O. S. and **J. G. Black.** Energy level studies on metallic vapors using a high temperature tungsten furnace—358(A)
——— Excitation of Cu(II) spectrum by positive Ne ions—925(A)
Duffendack, O. S. and H. L. Smith. Simultaneous ionization and excitation of molecules on collision with foreign ions—914(A)
Duffendack, O. S. (see Fox, G. W.)—921(A)
——— (see Wolfe, R. A.)—209(A)
Dunn, Hugh K. Changes in photoelectric threshold of Hg—693
Durbin, F. M. Dependence of the free path of potassium ions in various gases on their velocity—215(A)
Dushman, S., D. Dennison and **M. B. Reynolds.** Electron emission and diffusion constants for tungsten filaments containing various oxides—903(A)
Dushman, S. and **Jessie W. Ewald.** Electron emission from thoriated tungsten—857
Dymond, E. G. Electron scattering in He—433
Eastman, E. D. Book Review—494
Edwards, R. L. Magnetic properties of evaporated nickel and iron films—321
Eldridge, John A. Critical potentials of the spark lines of mercury—213(A)
———, **Alexander Ellett** and **Harry F. Olson.** Polarization of light excited by electron impact—207(A)

Ellett, Alexander. Impact polarization and the spinning electron—207(A)
———Polarization of resonance radiation in strong magnetic fields. Breadth of spectral lines—904(A)
——— (see Eldridge, John A.)—207(A)
Ellis, Joseph W. Infra-red absorption by the N-H bond; in aniline and alkyl anilines—356(A)
———New infra-red absorption bands in methane—750(A)
Ellsworth, Vivian M. and **J. J. Hopfield.** Oxygen bands in the ultra-violet—79
Epstein, Paul S. Magnetic dipole in Schroedinger's theory—750(A)
———Remark on the theory of the Trouton and Noble experiment—753(A)
Erikson, Henry A. Dependence of ionic mobility on the nature of the medium—369(A)
———Nature of gaseous ions—215(A)
Ewald, Jessie W. (see Dushman, S.)—857
Ewell, Arthur W. Influence of electrolytic ions upon moisture of steam—912(A)

Farnsworth, H. E. Velocity distribution and 180° scattering of low velocity electrons from Fe—908(A)
Focke, A. E. (see Blake, F. C.)—206(A)
Foote, Paul D. Ionization of Hg vapor by 2537—609(A)
——— (see Mohler, F. L.)—141
Foster, J. Stuart. Theory of the Stark effect in the arc spectra of helium—916(A)
——— and **W. Rowles.** The Stark effect in neon—925(A)
Fowle, E. S. (see Pienkowsky, A. T.)—910(A)
Fox, G. W., O. S. Duffendack and E. F. Barker. Excitation of the spectrum of CO_2—921(A)
Frank, N. H. Propagation of electromagnetic waves along coaxial cylindrical conductors separated by two dielectrics—365(A)
Franklin, William S. Significance and scope of the idea of frequency in physics—362(A)
Frayne, John G. and **Charles W. Jarvis.** Stages in excitation of spectrum of In—357(A), 673
Fredrickson, W. R., William W. Watson and **J. Rinker.** Na and K absorption bands—917(A)
Friauf, James B. Crystal structure of magnesium di-zincide—34, 353(A)

Gale, Henry G. and **George S. Monk.** Band spectrum, continuous emission, and continuous absorption of fluorine gas—211(A)
Galli-Shohat, N. Refraction in moving media—906(A)
Gartlein, C. W. Arc spectrum of Ge—357(A)
Germer, L. G. (see Davisson, C.)—908(A)
Gibbs, R. C. and **H. E. White.** Some relations in the spectra of stripped atoms—359(A)
———Two electron multiplets of first and second long periods—359(A)
———Multiplets in two electron systems of the first long period—426
———Multiplets in the spectra of Cr(III) and Mn (III)—917(A)
———Multiplets in the spectra of V(III)—606(A)
———Multiplets in the three electron systems of the first long period—655
Gibbs, R. C., D. T. Wilber and **H. E. White.** Terms arising from similar and dissimilar electrons—790, 917(A)
Gibson, K. S. (see Davis, Raymond)—916(A)
Gish, O. H. (see Rooney, W. J.)—905(A)
Gortner, Ross Aiken. Book Reviews—198, 348
Gould, King E. (see Bush, V.)—337
Gray, J. A. and **B. W. Sargent.** Absorption of beta-rays—351(A)

Ham, W. R. Equations for thermionic emission—607(A)
———Interpretation of data dealing with thermionic emission—364(A)
———Reflection of electrons from Mo—908(A)
Hamer, Richard and **Surain Singh.** Critical potentials of Cu—901(A)
———Critical potentials of Fe—608(A)
Hanson, R. L. Photoelectromotive force in selenium—924(A)
Harnwell, Gaylord P. Evidence for collisions of the second kind in the rare gases—608(A)
———Inelastic collisions in ionized gas mixtures—611(A)
———Ionization by collisions of the second kind in mixtures of hydrogen and nitrogen with the rare gases—830, 906(A)
———Ionization by collisions of the second kind in the rare gases—683
Harkins, William D. and **H. A. Shadduck.** The synthesis and disintegration of atoms as shown by an application of the Wilson, cloud-track method—207(A)
Harrington, E. A. X-ray diffraction measurements on some of the pure compounds concerned in the study of Portland cement—353(A)
Harrington, G. F. and **A. M. Opsahl.** Technique of the Dufour cathode ray oscillograph for the study of short time occurrences—364(A)
Harrison, J. R. Subfundamental piezo-electric vibrations in quartz plates—366(A)
———Theory and applications of low frequency piezo-electric vibrations in quartz plates—617(A)

Hartig, H. E. and **H. B. Wilcox.** Absolute method for measuring the velocity of fluids—485
Hartsough, R. C. Shielding from vibrations—910(A)
Havighurst, R. J. Electron distribution in the atoms of crystals. Sodium chloride and lithium, sodium and calcium fluorides—1
Haworth, F. E. (see Bozorth, Richard M.)—223
Heaps, C. W. Hall effect in Bi with small magnetic fields—332
Henderson, Joseph E. Pseudo photographic effect of slow electrons—360(A)
Hepburn, Ann B. Carbon monoxide band excitation potentials—212(A)
Hertel, K. L. A study of the polarization of light from hydrogen canal rays—214(A), 848
Herzfeld, K. F. Atomic properties which make an element a metal—701
Heyl, Paul R. Redetermination of the Newtonian constant of gravitation—910(A)
Hidnert, Peter and W. T. Sweeney. Thermal expansion of graphite—371(A)
———Thermal expansion of beryllium—616(A)
———Thermal expansion of some nickel steels—911(A)
Hoag, J. Barton. Extreme ultra-violet spectra using large angles of incidence—208(A)
Hopfield, J. J. Absorption spectra in the extreme ultra-violet—356(A)
———Some unclassified lines of oxygen in the ultra-violet—923(A)
——— (see Birge, R. T.)—356(A)
——— (see Ellsworth, Vivian M.)—79
——— and **R. T. Birge.** Ultra-violet absorption and spectra of CO—922(A)
Horovitz, Karl. Investigation of metal films by x-ray analysis—352(A)
———Determination of the surface area of adsorbers—617(A)
Houston, William V. A compound interferometer for fine structure work—210(A), 478
———Interferometer measurements on the Balmer series—749(A)
———Fine structure of the helium arc spectrum—749(A)
Hoyt, F. C. Book Review—197
Hubbard, K. H. (see Carman, A. P.)—217(A), 299
Huff, Thomas E. (see Butts, Donald C. A.)—219(A)
Hughes, C. W. (see Coblentz, W. W.)—365(A)
Hughes, A. Ll. and **L. W. Jones.** Distribution of energy among electrons rebounding from He atoms—214(A)
Hughes, A. Ll. and **A. M. Skellett.** Hot Wire vacuum gauge—365(A)
———Dissociation of hydrogen by electrons—907(A)
Hulbert, E. O. Absorption of radio waves in the upper atmosphere—365(A), 706
——— (see Crew, W. H.)—609(A), 843
Hull, Albert W. and **J. M. Hyatt.** Secondary electron emission from Mo—214(A)
Hunt, F. L. X-rays of long wave-length from a ruled grating —919(A)
Hulthèn, E. Band spectrum of calcium hydride—97
Hutchisson, Elmer. Energy of the crossed-orbit model of the hydrogen molecule—270
———Quantum theory of the specific heat of HCl—360(A)
Hyatt, J. M. Secondary electron emission produced by positive Cs ions—214(A)
——— (see Hull, Albert W.)—214(A)

Ives, Herbert E. and **G. R. Stilwell.** Photoelectric emission as a function of composition in Na-K alloys—252, 363(A)
Jarvis, Charles W. Ionization and resonance potentials in Ga and In—442
——— (see Frayne, John G.)—357(A), 673
Jauncey, G. E. M. Intensity of reflection of x-rays by crystals and the Compton effect—206(A)
——— Intensity of scattered x-rays and the Compton effect—605(A)
———Theory of the intensity of scattered x-rays—757
Jenkins, Francis A. Line spectra of isotopes of Hg and Cl—50
———Structure and isotope effect in the alpha bands of BO—921(A)
——— (see Kemble, E. C.)—607(A)
———, **Henry A. Barton** and **Robert S. Mulliken.** Beta bands of NO—211(A)
Johnson, E. H. Many-lined spectrum of sodium hydride—85
Johnson, J. B. Thermal agitation of electricity in conductors—367(A)
Johnson, Thomas H. Absolute ionization vacuum gauge—610(A)
Jones, Arthur Taber. Nodal lines of bells—616(A)
Jones, Ernest J. Excitation of Hg vapor by positive ions—611(A)
Jones, L. T. and A. M. Cravath. Neutralization of the deflecting field in a Braun tube with external electrodes—871
Jones, L. T. (see McCarty, L. E.)—880
Jones, L. W. (see Hughes, A. Ll.)—214(A)
Jones, T. J. Probability of ionization of Hg vapor by electron impact—822

Kaplan, Joseph. Duration of atomic hydrogen—920(A)

Karapetoff, Vladimir. Mechanical forces between electric currents and saturated magnetic fields—367(A)
———Formal unification of gradient, divergence, and curl, by means of an infinitesimal operational volume—914(A)
Kegerreis, Roy. Heat energy of x-rays—775
Kemble, E. C. and **F. A. Jenkins.** Quantitative test of Hund's theory of doublet bands of the OH type—607(A)
Kennard, E. H. Excitation of fluorescence in fluorescein—466
Kent, Norton A., Lucien B. Taylor and **Hazel Pearson.** Fine structure of the Balmer lines—748(A)
Kenty, Carl and Louis A. Turner. Surface layers produced by activated nitrogen.—914(A)
Keys, David A. Note on the auroral green line 5577—209(A)
Kimball, A. L. and **D. E. Lovell.** Internal friction in solids—616(A)
King, Arthur S. Spectra of the high-current vacuum arc—359(A)
King, Louis Vessot. On a gyromagnetic electron theory of the Compton effect—919(A)
Kingsbury, B. A. Direct comparison of the loudness of pure tones—373(A), 588
Kinsey, E. L. (see Wood, R. W.)—917(A)
Kirkpatrick, Paul. Polarization factor in x-ray reflection—632
Kleeman, Richard D. General theory of the electrical properties of surfaces of contact—368(A)
———Absolute zero of the externally controllable entropy and internal energy of a substance or mixture—369(A)
———Properties of substances and mixtures in the condensed state at the absolute zero of temperature—614(A)
———Relations in connection with the reversible mixing of substances in the condensed state at absolute zero—912(A)
Klein, Elias. Constancy of the flashing period of a neon glow-lamp—610(A)
Knudsen, V. O. Measurement of sound-absorption in a room—753(A)
Kollar, L. R. Effect of oxygen on photoelectric emission from potassium—902(A)
Krefft, Hermann E. O and N energy levels in the secondary emission of hot tungsten—908(A)
Kronig, R. de L. Book Review—601
——— and **I. I. Rabi.** Symmetrical top in the undulatory mechanics—262
Kunz, Jacob. Theory of the specific heat of methane—220(A)
———Resonance method for the determination of the universal constant of gravitation—910(A)
——— (see Tykocinski-Tykociner, J.)—904(A)
Kurrelmeyer, B. Optical absorption and photoelectric conductivity of sulphur crystals—615(A)

Laird, Elizabeth R. Absorption in region of soft x-rays—41
———Reflection of soft x-rays—605(A)
Lampland, C. O. (see Coblentz, W. W.)—372(A)
Langer, R. M. Charge density in the new mechanics—924(A)
Langmuir, Irving. (see Tonks, Lewi)—524, 614(A)
Lansing, William D. An electronic theory of passivity—216(A)
Laporte, O. Screening constants from optical data—650
——— (see Sommerfeld, A.)—208(A)
Lawrence, Ernest O. Length of radiation quanta—361(A)
———Ultra-ionization potentials of Hg—609(A)
——— (see Beams, J. W.)—357(A), 361(A), 903(A)
——— and **J. W. Beams.** The instantaneity of the photoelectric effect—903(A)
Lemon, Harvey B. Some laboratory observations bearing on the spectra of comets—210(A)
Levin, Aaron (see Meyer, Charles F.)—923(A)
Libman, E. E. Surface tensions of the molten elements as functions of temperature. I. Cu—911(A)
Lilienfeld, J. E. and **C. H. Thomas.** High pressure powder contact rectifier—367(A)
Linder, Ernest G. Thermoelectric effect in single crystal zinc—221(A), 554
Lindsay, George A. (see Van Dyke, George D.)—205(A)
Lindsay, R. B. Carbon atom model and the structure of diamond—497
———Note on "pendulum" orbits in atomic models—612(A)
Little, Noel C. Thermomagnetic effect in gases—901(A)
Loeb, Leonard B. Mobilities of ions in hydrogen gas mixtures and the constitution of the ion—751(A)
Loomis, F. W. Correlation of the fluorescent and absorption spectra of iodine—112
———New series in the spectrum of fluorescent iodine—355(A)
———Vibrational levels in the blue-green band system of Na—607(A)
Lord, James. (see Blake, F. C.)—206(A)
Loughridge, D. H. Direction of photoelectric emission—751(A)
Lovell, D. E. (see Kimball, A. L.)—616(A)
Lubovitch, Vladimir P. Infrared spectrum of Hg—355(A)

MacDougall, F. H. Book Reviews—494, 495, 602
MacMahon, A. M. New measurements upon the light sensitiveness of crystalline selenium—219(A)
———The significance of photoelectric conduction in crystals—902(A)
MacNair, Walter A. Secondary radiation and polarization of resonance radiation in Cd—677
———Zeeman effect of the fine structure components of λ2536 of Hg—915(A)
——— (see Brickwedde)—916(A)
Martin, John R. Magnetic properties of iron in high frequency alternating current fields—906(A)
Masius, Morton. Calculation of changes of function involving factorials as applied to entropy calculations—613(A)
McCarty, L. E. and **L. T. Jones.** Index of refraction of water for short continuous waves—880
McCurdy, W. H. Fine structure of the mercury line 3650A—915(A)
McDonald, Frank C. An investigation of some hydrocarbon bands—212(A)
McDowell, Louise S. and **Hilda Begeman.** Correlation between power loss, dielectric constant and conductivity of various glasses—367(A)
McKeehan, L. W. Iron crystals—920(A)
———Book Reviews—745, 746, 894
McKinstry, A. (see Morton, W. B.)—192
McLennan, J. C. and **I. Walerstein.** Fluorescence spectra in metallic vapours excited by the light in the mercury arc—208(A)
Meggers, W. F. and **F. M. Walters, Jr.** Absorption spectra of Fe, Co and Ni—358(A)
Meggers, W. F. (see Russell, Henry Norris)—606(A)
Mendenhall, H. E. Vacuum switch—754(A)
Meyer, Charles F. and **Aaron Levin.** Infrared absorption spectra of C_2H_2, C_2H_4, and C_2H_6—923(A)
Miller, Dayton C. Report on the ether-drift experiments at Cleveland in 1927—924(A)
Miller, Frederic H. Resonance in alternating currents containing a single harmonic—546
Miller, L. F. Relation of heat transmission to humidity in insulating materials—370(A)
Millikan, R. A. and **I. S. Bowen.** Relationships in the spectra of the first row of the periodic table—750(A)
Mitchell, A. C. G. and **R. G. Dickinson.** Effect of added gases on ammonia decomposition by optically excited Hg vapor—751(A)
Mohler, F. L. Excitation of spectra by atomic hydrogen—354(A), 419
——— and **Paul D. Foote.** Electron collisions in Co—141
Monk, George S. (see Gale, Henry G.)—211(A)
Mooney, Melvin. New electrophoretic mobility formula—217(A)
———New electrophoresis cell—218(A)
Morehouse, W. B. X-ray absorption and valence—924(A)
———Effect of chemical combination on x-ray absorption—765
Morrow, Roger M. (see Stewart, G. W.)—919(A)
Morse, P. M. (see Compton, K. T.)—909(A)
Morton, W. B. and **A. McKinstry.** Continuous motion produced by vibration—192
Mueller, Hans. Activity of monovalent ions—216(A)
——— (see Allis, W. P.)—361(A)
Mulliken, Robert S. Intensity relations and electronic states in spectra of diatomic molecules—211(A)
———Electronic states and band spectrum structure in diatomic molecules: III, Intensity relations—391
———Electronic states and band spectrum structure in diatomic molecules: IV, Hund's theory; second positive nitrogen and Swan bands; alternating intensities—637
———Intensity relations and band structure in bands of the violet CN type—923(A)
———Band structure and intensities, atomic and molecular electronic states, in diatomic hydrides—921(A)
——— (see Jenkins, Francis A.)—211(A)
Murnaghan, Francis D. and **Harold A. Wheeler.** Analysis and applications of wave-filter determinants—914(A)
Muskat, Morris (see Smith, Alpheus W.)—663

Nathanson, J. B. Variation with state of the optical constants of Cs—369(A)
Nicholas, Warren W. A system of structures for atomic nuclei—612(A)
———X-ray isochromats of Cu taken in different directions relative to the cathode stream—619
Nielsen, Walter M. Dissociation of HCl by positive ion impact—907(A)
Nusbaum, C. Magnetic susceptibility of single-crystal elements—370(A)
———Magnetic susceptibility of single-crystal metals—905(A)
Nye, Arthur W. Measurement of wave-length of light in water—753(A)
Nyquist, H. Thermal agitation in conductors—614(A)

Olson, Harry F. Polarization of λ2537 of Hg—207(A)
——— (see Eldridge, J. A.)—207(A)

Opsahl, A. M. (see Harrington, G. F.)—364(A)
Ostenson, Floyd C. and **S. H. Anderson.** End corrections of pipes as a function of frequency—753(A)

Page, Leigh. Book Reviews—349, 896
Palmer, Frederick, Jr. (see Butts, Donald C. A.)—219(A)
Parmley, T. J. Photoelectric threshold of Bi crystals—902(A)
Pauling, Linus. Influence of a magnetic field on the dielectric constant of a diatomic dipole gas—145
———Electron affinity of hydrogen and the second ionization potential of lithium—285
Pearson, Hazel. (see Kent, Norton A.)—748(A)
Pease, C. S. (see Smith, Alpheus W.)—355(A)
Perkins, B., Jr. (see Watson, William W.)—921(A)
Phipps, T. E. and **John B. Taylor.** Magnetic moment of the hydrogen atom—218(A), 309
Phipps, T. E. (see Taylor, John B.)—904(A)
Pienkowsky, A. T. and **E. S. Fowle.** Variations of gold-plated screw knob weights with atmospheric humidity—910(A)
Piersol, Robert J. Influence of temperature on selenium photosensitivity—362(A)
———Relation between light intensity and photocurrent in selenium—902(A)
Plyler, E. K. Infra-red reflection spectra of some carbonates—923(A)
Podolsky, Boris. On King's classical theory of atomic structure 750(A)
Poindexter, F. E. New instrument for measuring surface tension—221(A)
Pomeroy, William C. Quantum analysis of band spectrum of aluminum oxide—59
Pool, M. L. Post-arc conductivity and metastable states in Hg—610(A)
———Residual ions and critical restriking potential in Hg arcs—915(A)
Purks, J. H. and **C. M. Slack.** Possible dependence of frequency of characteristic x-radiation on the temperature of the target—352(A)

Rabi, I. I. Principal magnetic susceptibilities of crystals—174
——— (see Kronig, R. de L.)—262
Race, Hubert H. Electric absorption currents in solid dielectrics—913(A)
Rashevsky, N. Theory of the heats of fusion—220(A)
Ray, Satyendra. Note on the plane wave of a gas—892
Reynolds, N. B. (see Dushman, S.)—903(A)
Reyerson, L. H. Book Review—746
Richardson, Burt and **Paul.** Measuring the evaporation from a body of water—755(A)
Richtmeyer, F. K. and **L. S. Taylor.** Relative probabilities of the photoelectric emission of electrons from Ag to Au—353(A)
———Further test of the theories of absorption of x-rays—606(A)
Rinker, J. (see Fredriokson, W. R.)—917(A)
Roberds, W. M. Resistance of copper wires at very high frequencies—165
Roebuck, J. R. Book Review—898
Rogers, R. A. M series x-ray absorption spectra of Os, Ir, and Pt—205(A)
Rooney, W. J. and **O. H. Gish.** Results of earth resistivity surveys in connection with the study of the earth currents at Watheroo, Western Australia and Ebro, Spain—905(A)
Rowles, W. (see Foster, J. Stuart)—925(A)
Rudnick, Philip. (see Watson, William W.)—413
Rudy, Richard. Metastable neon and argon—359(A)
Rusk, Rogers D. Resonance glow in hydrogen discharge tube—213(A)
———The 29 volt critical potential of hydrogen—354(A)
———Combination of hydrogen and oxygen by electric discharges and x-rays—907(A)
Russell, Henry Norris. Calculation of spectroscopic terms derived from equivalent electrons—782
——— and **W. F. Meggers.** Analysis of the arc and spark spectra of Sc—606(A)
Russell, H. W. Potential of photoactive cells containing fluorescent electrolytes—615(A)

Sagui, Cornelio L. Theory of the magnetic nature of gravity—371(A)
———Theory of the magnetic nature of gravity and the Balmer series—618(A)
———Theory of the magnetic nature of gravity and electrons—906(A)
Sargent, B. W. (see Gray, J. A.)—351(A)
Sawyer, R. A. and **F. R. Smith.** Spectra of boron—357(A)
Schneider, W. A. Actino-electric effects in argentite—363(A)
Seemann, Herman E. Thermal conductivity of fused quartz as a function of temperature—616(A)
Shadduck, H. A. (see Harkins, William D.)—207(A)
Shapley, Harlow. Book Review—894
Shenstone, A. G. Spark spectrum of Cu II—209(A), 380
———Spark spectrum of Ni—917(A)

Simon, A. W. On the electrostatics of the thunderstorm—754(A)
Singh, Surain (see Hamer, Richard)—608(A), 901(A)
Skellett, A. M. (see Hughes, A. Ll.)—365(A), 907(A)
Slack, C. M. (see Purks, J. H.)—352(A)
Smede, L. Temperature variations in wires heated by alternating current—614(A)
Smith, Alpheus W., Cecil E. Boord and **C. S. Pease.** The absorption of ultra-violet light by organic vapors—355(A)
Smith, Alpheus W. and **Morris Muskat.** Absorption spectra of Ga, In, Mn, Cr, Ni, and Co in under-water sparks—663
Smith, F. R. (see Sawyer, R. A)—357(A)
Smith, H. L. (see Duffendack, O. S.)—914(A)
Smith, Sinclair. A vertical seismometer—755(A)
Smith, T. Townsend. Effect of a variation from the condition for achromatism in lenses—220(A)
Solt, Irvin H. Magnetic moment of He and H_2—904(A)
Sommer, L. A. Zeeman effect and structure of arc spectra of Cu and Rh—358(A)
Sommerfeld, A. and **O. Laporte.** Spectroscopic interpretation of the magneton numbers in the iron group—208(A)
Sorenson, Royal W. Effect of oil in storage on lightning discharge—754(A)
Spencer, R. C. Method of least squares vs. the arithmetic method of obtaining the slope of a straight line—909(A)
Stebbins, Joel. Book Review—895
Stewart, G. W. Theory of the Herschel-Quincke tube—220(A)
———Book Review—494
——— and **Roger M. Morrow.** Molecular space array in liquid primary normal alchohols: the cybotatic state—919(A)
Stilwell, G. R. (see Ives, Herbert E.)—252, 363(A)
Stinchcomb, G. A. and E. F. Barker, Fine structure of three infrared absorption bands of NH_3—213(A)
Stuhlman, Otto. Possible relation between radiation and ionization potentials of iron—354(A)
Swann, W. F. G. Measurements of the variation of residual ionization in air with pressure at different altitudes—372(A)
———Origin of the magnetic fields of sun spots—905(A)
Sweeney, W. T. (see Hidnert, Peter)—371(A), 616(A), 911(A)
Swenson, David F. Book Review—197

Takeuchi, T. Scattering of particles by an Einstein center—186
Tate, John T. Book Reviews—346, 602, 747
Taylor, John B. and **T. E. Phipps.** Magnetic moment of atomic iodine—904(A)
Taylor, John B. (see Phipps, T. E.)—218(A), 309
Taylor, Lauriston. A type of oscillation hysteresis—617(A)
Taylor, Lucien B. (see Kent, Norton A)—748(A)
Taylor, L. S. (see Richtmyer, F. K.)—353(A), 606(A)
Taylor, Paul B. Theory of cell with liquid junction—369(A)
Terry, Earle M. Factors affecting the constancy of quartz piezo-electric oscillators—366(A)
Thomas, C. H. (see Lilienfeld, J. E.)—367(A)
Tonks, Lewi. Space charge as a cause of negative resistance in a triode—913(A)
——— and **Irving Langmuir.** On the surface heat of charging—524, 614(A)
Tschudi, E. W. Spectral intensity distribution in a hydrogen discharge—354(A)
Turner, Louis A. (see Kenty, Carl)—914(A)
Tykocinski-Tykociner, J. Precise determination of frequency by means of piezo-electric oscillators—366(A)
———Shielded oscillator for Hertzian waves—217(A)
———Velocity selector for atomic rays —611(A)
——— and **J. Kunz.** Method of measuring the distribution of magnetic fields—904(A)

Valasek, Joseph. Relative intensities of some lines in the Hg spectrum—817
———Book Reviews—492, 496, 603, 899, 900
Valasek, Leila M. Transformation period of the initial positive air ion—542
Vallarta, M. S. On the condition of validity of macromechanics—613(A)
Van Dyke, George D. and **George A. Lindsay.** X-ray *L* absorption edges of elements Sn to Ru inclusive—205(A)
Van Vleck, J. H. A general proof of the Langevin-Debye formula and the susceptibilities of O_2 and NO—613(A)
——— Dielectric constants and magnetic susceptibilities in the new quantum mechanics—727
——— Book Reviews—202, 491
Van Voorhis, C. C. and **K. T. Compton.** Heats of condensation of electrons and positive ions on Mo—909(A)

Wait, G. R. On the effects of dust, smoke, and relative humidity upon the potential gradient and the positive and negative conductivities of the atmosphere—372(A)

Wait, G. R. Magnetic permeability of iron and magnetite in high frequency alternating fields—566
Walerstein, I. (See McLennan, J. C.)—208(A)
Walters, F. M., Jr. (see Meggers, W. F.)—358(A)
Warburton, F. W. Hall effect and resistance of sputtered Te films—905(A)
Waterman, A. T. Electrical resistance of metals as a function of pressure—368(A)
Watson, E. C. The velocity and number of the photoelectrons ejected by x-rays as a function of the angle of emission—751(A)
——— Spacial distribution of the photoelectrons ejected by x-rays—752(A)
——— Explanation of Whiddington's rule for x-ray electrons—919(A)
Watson, F. R. A method for determining sound transmission—925(A)
——— Optimum conditions for music in rooms—220(A)
Watson, William W. and **B. Perkins, Jr.** Zeeman effect in AgH, AlH, ZnH and MgH bands—921(A)
Watson, William W. and **Philip Rudnick.** Rotational terms in the MgH bands—413
Watson, William W. (see Frederickson, W. R.)—917(A)
Weatherby, B. B. (see Wolf, A.)—135
Webster, D. L. Book Review—346
Weigle, J. J. Effect of a magnetic field on the dielectric constant—362(A)
Welo, L. A. and **O. Baudisch.** Magnetic moments of iron in complex salts—612(A)
Welsh, George B. The periodicity of photoelectric thresholds—615(A)
Wenner, Frank. Principle governing the distribution of current in systems of linear conductors—218(A)
Wheeler, Harold A. Theory of the shot effect—903(A)
——— (see Murnaghan, Francis D.)—914(A)
White, H. E. (see Gibbs, R. C.)—359(A), 426, 606(A), 917(A), 655, 917(A), 790
Whitney, W. T. Michelson-Gale earth-tide experiment repeated in Pasadena, California—755(A)
Wiebusch, C. F. (see Brown, S. L.)—887
Wilber, D. T. (see Gibbs, R. C.)—917(A), 790
Wilcox, H. B. (see Hartig, H. E.)—485
Wilkins, T. R. New theory of the origin of the actinium series—352(A)
Willard, G. W. (see Campbell, G. C.)—913(A)
Williams, E. H. Magnetic susceptibility of rare earth metals—218(A)
Williams, S. R. An unusual magnetostrictive effect in Monel metal—370(A)
Winans, J. G. Collisions of the second kind between zinc and mercury atoms—213(A)
Winchester, George. Variation of surface tension of oils with the temperature—911(A)
Wissink, G. M. (see Woodrow, Jay W.)—219(A)
Witmer, Enos E. Quantization of the rotational energy of the polyatomic molecule by the new wave mechanics—362(A)
——— Rotational and vibrational specific heat of a diatomic gas, the molecules of which have a doublet *P* normal state—918(A)
Wolf, A. and B. B. Weatherby. Absorption coefficient of helium for its own radiation—135
Wolfe, R. A. and O. S. Duffendack. Excitation of arc spectrum of N—209(A)
Wood, R. W. Physical and biological effects of high frequency sound waves of great intensity—373(A)
——— Demonstration of an improved form of Rijke tube of high efficiency. A lecture experiment in acoustics—373(A)
——— **and E. L. Kinsey.** The fluorescence of Na vapor—917(A)
Woodrow, Jay W. and **G. M. Wissink.** Fluorescence and chemiluminescence of cod liver oil—219(A)
Worthing, A. G. Some observations on the nature of the nitrogen afterglow—907(A)

Zeleny, John. Striated discharge in H_2 and He—609(A)
Zemansky, Mark W. Diffusion of imprisoned resonance radiation in Hg vapor—513
Zimmerman, E. E. Effect of temperature on polarization capacity and resistance for Au and Pt electrodes in different concentrations of sulphuric acid and at different audible frequencies—913(A)
Zinszer, Harvey A. Shadowgraph method as applied to a study of the electric spark—752(A)
Zumstein, R. V. Absorption spectrum of antimony vapor—209(A)
Zwicky, F. Phenomena depending on the change of elastic frequencies in solid bodies with pressure—579, 754(A)

ANALYTIC SUBJECT INDEX TO VOLUME 29

Reference with (A) are merely to abstracts of papers presented at meetings of the Physical Society.

Absorption of light (see also Electrical oscillations, Spectra, x-rays)
By aniline and alkyl anilines, infra-red, J. W. Ellis—356(A)
By CH_4, new infra-red bands, J. W. Ellis—751(A)
By fluorescein, relation to fluorescence, E. H. Kennard—466
By He for its own radiation, A. Wolf, B. B. Weatherby—135
By kunzite and hiddenite, colored by x-rays, P. L. Bayley—353(A)
By liquified gases, F. G. Brickwedde and W. A. MacNair—916(A)
By organic vapors, in ultra-violet, A. W. Smith, C. E. Boord, C. S. Pease—355(A)
By sulphur crystals, relation to photoelectric conductivity, B. Kurrelmeyer—615(A)

Acoustics
absorption in room, measurement, V. O. Knudsen —753(A)
End corrections of pipes as function of frequency, F. C. Ostenson, S. H. Anderson—753(A)
Herschel-Quincke tube, theory, G. W. Stewart—220(A)
Loudness of pure tones, comparison, B. A. Kingsbury—373(A), 588
Method for measuring velocity of fluids, H. E. Hartig, H. B. Wilcox—485
Nodal lines of bells, A. T. Jones—616(A)
Optimum conditions for music in rooms, F. R. Watson—220(A)
Plane waves in gases, S. Ray—892
Resolving power of ears, A. L. Bennett—911(A)
Rijke tube of high efficiency, demonstration, R. W. Wood—373(A)
Transmission of sound, method for determining, F. R. Watson—925(A)
Ultrasonic waves, physical and biological effects, R. W. Wood—373(A)

Actino-electric (see Photoelectric)

Activated gases (see also collisions of second kind, Metastable atoms)
Active nitrogen, afterglow, A. G. Worthing—907(A)
Active nitrogen, electric properties and nature, P. A. Constantinides—215(A)

Activated gases (cont.)
Active nitrogen, surface layers produced by, C. Kenty, L. A. Turner—914(A)

Activity, chemical
Of monovalent ions, H. Mueller—216(A)

Adsorption
Of Cs on W, life history, J. A. Becker—364(A)
Surface area of adsorbers, determination, K. Horovitz—617(A)
Surface layers on W, produced by active nitrogen, C. Kenty, L. A. Turner—914(A)

Aerodynamics
Motion of airship in variable horizontal winds, H. Bateman—755(A)

Affinity, electron
Of H_2, L. Pauling—285

Alpha particles
Scattering by Einstein center, T. Takeuchi—186

Arcs
High-current, vacuum, spectra, A. S. King—359 (A)
In H_2, 29 volt critical potential, R. D. Rusk—354(A)
In Hg vapor, post-arc conductivity, M. A. Pool—610(A)
In Hg vapor, residual ions and restriking potentials, M. L. Pool—915(A)
In N_2-He mixture, spectra, R. A. Wolfe, O. S. Duffendack—209(A)
Metallic, in vacuo, striking potentials, S. H. Anderson—750(A)

Atmospheric electricity
Cosmic aspects, L. A. Bauer—371(A)
Effects of dust, smoke, and humidity, G. R. Wait —372(A)

Atomic radii
Of Pt and Mg atoms, R. M. Bozorth, F. E. Haworth—223

Atomic rays
Velocity selector, J. Tykocinski-Tykociner—611 (A)

Atomic structure

Breakdown at high pressures, P. W. Bridgman—188

Energy level diagrams, comprehensive form, R. T. Birge—922(A)

Electron distribution from x-ray measurements, R. J. Havighurst—1

Electron distribution from x-ray measurements, J. A. Bearden—20

King's classical theory, B. Podolsky—751(A)

Metastable atoms, explanation of long life, G. Breit—361(A)

Of carbon, structure of diamond, R. B. Lindsay—497

Pendulum orbits, R. B. Lindsay—612(A)

Structures of nuclei, W. W. Nicholas—612(A)

Aurora

Auroral green line 5577, from discharge in He-O_2 and A-O_2 mixtures, D. A. Keys—209(A)

Beta-rays

Absorption in Al, C, Cu, Pb, and Sn, J. A. Gray, B. W. Sargent—351(A)

Book Reviews

Alexander, Jerome (editor); Colloid Chemistry—Theoretical and Applied—198

Ambronn, Hermann, and Frey, Albert; Polarisations-Mikroscop, seine Anwendung in der Kolloidforschung und in der Farberei—492

ten Bruggencate, P.; Sternhaufen—894

Brunet, Pierre.; Les Physiciens Hollandais et la méthode Experimentale en France au XVIII• Siecle—197

Callender, H. L.; Enlarged Mollier Diagram for Saturated and Superheated Steam—898

Clark, George L.; Applied X-rays—746

Crandall, Irving B.; Theory of Vibrating Systems and Sound—494

Darrow, Karl K.; Introduction to Contemporary Physics—346

Du Noüy, P. Lecomte; Surface Equilibria of Biological and Organic Colloids—495

Einstein, Albert; Investigations on the Theory of the Brownian Movement—747

Eyraud, Henri; Les Equations de la Dynamique de L'Ether—349

Forestier, A.; L'Enérgie Rayonnante—603

Franck, J., and Jordon, P.; Anregung von Quantenspruengen durch Stoesse—346

Fenkel, J.; Lehrbuch der Elektrodynamik Bd. I—896

Gehrcke, E. (editor); Handbuch der Physikalischen Optik Vol. I First half—899

Gehrcke, E. (editor); Handbuch der Physikalischen Optik Vol. II First half—900

Geiger, H. and Scheel, Karl; Handbuch der Physik. B. I. Geschichte der Physik; Vorlesungtechnik—346

Geiger, H., and Scheel, Karl; Handbuch der Physik, Bd. II. Elementare Einheiten und Ihre Messung—202

Geiger, H., and Scheel, Karl; Handbuch der Physik. Bd. IX. Theorien der Wärme—201

Geiger, H., and Scheel, Karl; Handbuch der Physik. Bd. XI. Anwendung der Thermodynamik—201

Geiger, H., and Scheel, Karl; Handbuch der Physik. Bd. XXIII. Quanten—202

Graetz, L.; Handbuch der Elektrizität und des Magnetismus. Bd. V—Lieferung I—200

Haas, Arthur; Die Welt der Atome—493

Hale, George Ellery; Beyong the Milky Way—496

v. Hevesy, Georg; Das Element Hafnium—602

Hinchelwood, C. N.; Thermodynamics (For Students of Chemistry)—494

Holborn, L., and von Angerer, E.; Handbuch der Experimental Physik Vol. I, Messmethoden und Messtechnik—199

Humphreys, W. J.; Fogs and Clouds—898

Juvet, G.; Mechanique Analytique et Théorie des Quanta—197

von Laue, M., and von Mises, R. (editors); Stereoscopic Drawings of Crystal Structures—899

Lewis, Gilbert N.; The Anatomy of Science—349

Liesegang, Raphael Ed.; Kolloidchemie—348

Mark, Herman; Die Verwendung der Röntgenstrahlen in Chemie und Technik. Bd. XIV—745

Mecke, Reinhard and Lambertz, Anton; Leitfaden der Praktischen Experimentalphysik für Vorlesung und Unterricht—896

Moss, Herbert; The Enlarged Heat Drop Tables—898

Müller-Pouillet; Lehrbuch der Physik. Bd. II—603

Müller-Pouillet; Lehrbuch der Physik. Bd. III, First half. Physikalische, chemische und technische Thermodynamik—897

Ostwald, Wolfgang; Practical Colloid Chemistry—746

Planck, Max; Treatise on Thermodynamics—747

Reilly, Joseph, Roe, William Norman and Wheeler, Thomas Sherlock; Physico-chemical Methods—494

Rideal, E. K.; An Introduction to Surface Chemistry—495

Russell, Henry Norris, Dugan, Raymond Smith and Stewart, John Quincy; Astronomy—895

Schroedinger, E.; Abhandlungen zur Wellenmechanik—601
Senter, George; Outline of Physical Chemistry—602
Smekal, Adolf; Allgemeine Grundlagen der Quantenstatistik und Quantentheorie—601
Sommerfeld, Arnold; Three Lectures on Atomic Physics—491
Spooner, Thomas; Properties and Testing of Magnetic Materials—894
Stoner, Edmund C.; Magnetism and Atomic Structure—348
Troland, Leonard T.; The Mystery of Mind—197
Tutton, A. E. H.; Crystalline Form and Chemical Constitution—491
Walsh, John W. T.; Photometry—496
Webster, D. L., Farwell, H. W., and Drew, E. R.; General Physics for Colleges—199
Wohlwill, Emil; Galilei und sein Kampf für die Copernicanische Lehre—492

Braun tube
With external electrodes, neutralization of field, L. T. Jones, A. M. Cravath—871

Canal Rays
Of hydrogen, polarization of light, K. L. Hertel—214(A), 848

Cathode fall
Theory, K. T. Compton, P. M. Morse—909(A)

Cells
Electrolytic with liquid junction, theory, P. B. Taylor—369(A)
Electrophoresis, new type, M. Mooney—218(A)

Charge density
Interpretation in new mechanics, R. M. Langer—924(A)

Chemical reaction
Combination of H_2 and O_2 by discharges and x-rays, R. D. Rusk—907(A)
Decomposition of NH_3 by excited Hg, effect of added gases, A. C. G. Mitchell, R. G. Dickinson—751(A)
Duration of atomic hydrogen, J. Kaplan—000(A)
Effect on x-ray absorption, W. B. Morehouse—924(A), 765

Chemiluminescence
Of cod-liver oil, J. W. Woodrow, G. M. Wissink—219(A)

Collisions of the second kind (see also Activated gases)
Between Zn and excited Hg atoms, J. G. Winans—213(A)
Between active nitrogen and iodine, P. Constantinides—215(A)
Decomposition of NH_3 by excited Hg, A. C. G. Mitchell, R. G. Dickinson—751(A)
Effect on diffusion of resonance radiation in Hg vapor, M. W. Zemansky—513
Evidence for, in the rare gases, G. P. Harnwell—608(A)
Excitation of Cu(II) spectrum by positive neon ions, O. S. Duffendack, J. G. Black—925(A)
Excitation of spectra by atomic hydrogen, F. L. Mohler—419, 354(A)
Inelastic collisions in ionized gas mixtures, G. P. Harnwell—611(A)
Ionization by, in rare gases, G. P. Harnwell—683
Ionization by, in mixtures of H_2 and N_2 with the rare gases, G. P. Harnwell—906(A), 830
Ionization and excitation by collisions with foreign ions, O. S. Duffendack, H. L. Smith—914(A)

Colloids
Electrophoretic mobility formula, M. Mooney—217(A)
Electrophoresis cell, new type, M. Mooney—218(A)

Comets
Spectra, N. T. Bobrovnikoff—210(A)
Spectra, laboratory observations, H. B. Lemon—210(A)

Compton effect (see x-rays, scattering)

Crystals
Photoelectric conduction, significance, A. M. MacMahon—902(A)
Theory of growth, W. P. Davey—206(A)

Crystals, single
of Fe, new method of producing, L. W. McKeehan—920(A)
Of Ni, scattering of electrons by, C. Davisson, L. H. Germer—908(A)
Of Zn, thermoelectric effect, E. G. Linder—221(A), 554
Of various elements, susceptibility, C. Nusbaum—370(A)

Crystal structure
Of diamond, theory, R. B. Lindsay—497
Of $MgZn_2$, J. B. Friauf—34, 353(A)
Of magnesium platinocyanide heptahydrate, R. M. Bozorth, F. E. Haworth—223
Of solid solutions of Cr and Ni and of Fe and Ni, F. C. Blake, J. Lord, A. E. Focke—206(A)

Cybotatic state
Molecular space array in primary normal alcohols, G. W. Stewart, R. M. Morrow—919(A)

Dielectric constants
Of air, determination by discharge method, A. P. Carman, K. H. Hubbard—217(A), 299
Of diatomic dipole gases, influence of magnetic field, L. Pauling—145
Of gases, effect of magnetic field, J. J. Weigle—362(A)
Of glasses, relation to power loss and conductivity, L. S. McDowell, H. Begeman—367(A)
Theory, in the new quantum mechanics, J. H. VanVleck—727

Dielectrics
Solid, electric absorption currents, H. H. Race—913(A)

Diffraction (see also x-rays)
Of soft x-rays by ruled grating, F. L. Hunt—919(A)

Diffusion
Of resonance radiation in Hg vapor, M. W. Zemansky—513
Of U, Th, Ce, Zr, Yt in hot tungsten, constants of, S. Dushman, D. Dennison, N. B. Reynolds—903(A)

Discharge of electricity in gases (see also Spark discharge)
Geiger counters, properties, R. D. Bennett—363(A)
In He-O_2, A-O_2 mixtures, spectra, D. A. Keys—209(A)
In H_2, resonance glow, R. D. Rusk—213(A)
In H_2, spectral intensity distribution, E. W. Tschudi—254(A)
In H_2 and He, pressure effects on striae, J. Zeleny—609(A)
In H_2, number of radiating atoms, W. H. Crew, E. O. Hulburt—843
In H_2, He, N_2, air, CO, CO_2, pressure effects on striae, L. H. Dawson—610(A)
In H_2-O_2 mixtures, rate of combination, R. D. Rusk—907(A)
Normal cathode fall, theory, K. T. Compton, P. M. Morse—909(A)
Pressures in long slim discharge tubes, W. H. Crew, E. O. Hulburt—609(A)

Discharge of electricity in high vacua
with intense electric field, C. Del Rosario—360(A)

Disintegration of atoms
As shown by Wilson cloud-tracks, W. D. Harkins, H. A. Shadduck—207(A)

Dissociation
Of H_2, by electron impact, A. Ll. Hughes, A. M. Skellett—907(A)
Of HCl, by positive ion impact, W. M. Nielsen—907(A)

Ears
Resolving power of the ears, A. L. Bennett—911(A)

Earth Currents
At Watheroo, western Australia, and Ebro, Spain, W. L. Rooney, O. H. Gish—905(A)

Earth tides
At Pasadena, W. T. Whitney—755(A)

Elastic oscillations
Continuous motion produced by, W. B. Morton, A. McKinstry—192
In crystals, shear mode, W. G. Cady—617(A)
In quartz, factors affecting constancy, E. M. Terry—366(A)
In quartz, subfundamentals, J. R. Harrison—366(A)
In solids, change with pressure, F. Zwicky—579, 755(A)

Electrical capacity
Polarization capacity for Au and Pt electrodes, E. E. Zimmerman—913(A)

Electrical conductivity and resistance
Of active nitrogen, P. A. Constantinides—215(A)
Of air condenser, high frequency, S. L. Brown, C. F. Wiebusch, M. Y. Colby—887
Of Cu wires, high frequency, W. M. Roberds—165
Of electrolytic cells with Au and Pt electrodes, E. E. Zimmerman—913(A)
Of elements, atomic properties which determine, K. F. Herzfeld—701
Of glasses, relation to power losses, L. S. McDowell, H. Begeman—367(A)
Of metals, effect of pressure, F. Zwicky—579, 755(A)
Of metals, effect of pressure, A. T. Waterman—368(A)
Of Se, light sensitiveness, A. M. MacMahon—219(A)
Of Se, light sensitiveness, R. J. Piersol—902(A)
Of Se, influence of temperature, R. J. Piersol—362(A)
Of Te films, and Hall effect, F. W. Warburton—905(A)

Electrical currents
Absorption currents in solid dielectrics, H. H. Race—913(A)
Distribution in systems of conductors, theory, F. Wenner—218(A)

Electrical measurements (see also Electrical conductivity)
At radio frequencies, S. L. Brown, M. Y. Colby —717
Determination of dielectric constant of air by discharge method, A. P. Carman, K. H. Hubbard—217(A), 299

Electrical oscillations and waves
Absorption of radio waves in upper atmosphere, E. O. Hulburt—365(A), 706
High frequency magnetic properties of Fe, J. R. Martin—906(A)
High frequency permeability of iron and magnetite, G. R. Wait—566
High frequency resistance of air condenser, S. L. Brown, C. F. Wiebusch, M. Y. Colby —887
High frequency resistance of Cu wire, W. M. Roberds—165
Measurements at radio frequencies, S. L. Brown, M. Y. Colby—717
Propagation along coaxial conductors, N. H. Frank—365(A)
Refractive index of water for short waves, L. E. McCarty, L. T. Jones—880
Resonance in alternating current circuits, F. H. Miller—546
Shielded oscillator for Hertzian waves, J. Tykocinski-Tykociner—217(A)
type of oscillation hysteresis, L. Taylor—617(A)

Electrolytes
Activity of monovalent ions, H. Mueller—216(A)
E. m. f. of cells with fluorescent electrolytes, H. W. Russell—615(A)
Polarization capacity and resistance for Au and Pt electrodes, E. E. Zimmerman—913(A)
Theory of cell with liquid junction, P. B. Taylor —369(A)
Theory of surfaces of contact, R. D. Kleeman —368(A)

Electromagnetic theory
Distribution of currents in linear conductors, F. Wenner—218(A)
Forces between currents and magnetic fields, V. Karapetoff—367(A)
Gyromagnetic electron theory of Compton effect, L. V. King—919(A)
King's theory of atomic structure, B. Podolsky —750(A)

Electromagnetic theory (cont.)
Origin of magnetic fields of sun spots, W. F G. Swann—905(A)
Propagation of waves along coaxial conductors, N. H. Frank—365(A)
Refraction in moving media, N. Galli-Shohat— 906(A)
Scattering by Einstein center, T. Takeuchi—186
Trouton-Noble experiment, P. S. Epstein—753(A)
Unification of grad, div, curl, V. Karapetoff—914 (A)

Electromotive force
At surfaces of contact, R. D. Kleeman—368(A)
In conductors, due to thermal agitation, J. B. Johnson—367(A)
In conductors, due to thermal agitation, H. Nyquist—614(A)
Photo-e. m. f. in Se, R. L. Hanson—924(A)

Electrons
Affinity of H_2 for, L. Pauling—285
Distribution in crystal atoms, R. J. Havighurst —1
Distribution in crystal atoms, J. A. Bearden—20
Heat of condensation on Mo, C. C. VanVoorhis, K. T. Compton—909(A)
Photographic effect, J. E. Henderson—360(A)
Pulling electrons out of metals, C. Del Rosario —360(A)
surface heat of charging, L. Tonks, I. Langmuir —524, 614(A)
Spinning, relation to impact polarization, A. Ellett—207(A)
Spinning, theory of Compton effect, L. V. King —919(A)
Velocity distribution, after passing diaphragms, R. H. Dalton, W. P. Baxter—248
Wave theory of, W. P. Allis, H. Mueller—361(A)

Electrons, energy states (see also Potentials, critical; spectra; spectroscopic terms)
Comprehensive energy level diagram, R. T. Birge—922(A)
In C atom, R. B. Lindsay—497
In CO, F. L. Mohler, P. D. Foote—141
In Cu, O. S. Duffendack, J. G. Black—358(A)
In diatomic molecules, R. S. Mulliken—211(A), 391, 637
In diatomic hydrides, R. S. Mulliken—921(A)
In In vapor, J. G. Frayne, C. W. Jarvis—357(A)
O and N levels in tungsten, H. E. Krefft—908(A)
Pendulum orbits, R. B. Lindsay—612(A)

Electrons, impacts, reflection, scattering
Impact polarization and spinning electron, A. Ellett—207(A)

Electrons, impacts, reflection, scattering (cont.)
Impact polarization, in Hg, J. A. Eldridge, A. Ellett, H. F. Olson—207(A)
In CO, critical potentials, F. L. Mohler, P. D. Foote—141
In He, energy distribution of scattered electrons, A. Ll. Hughes, L. W. Jones—214(A)
In He, energy and angular distribution of scattered electrons, E. G. Dymond—433
On Fe, velocity distribution of secondaries, H. E. Farnsworth—908(A)
On Mo, number and energy of secondaries, W. R. Ham—908(A)
On Mo, number of secondaries as function of incident velocity, A. W. Hull, L. M. Hyatt—214(A)
On Ni, single crystal, angular distribution of scattered electrons, C. Davissson, L. H. Germer—908(A)

Electrons in metals
Effects due to thermal agitation, H. Nyquist—614(A)
E. m. f. due to thermal agitation, J. B. Johnson—367(A)

Electrons, photoelectric (see Photoelectric effect)

Electrons, secondary (see also Electron impacts)
Produced by positive Cs ions, J. M. Hyatt—214(A)

Electrophoresis
Cell, new type, M. Mooney—218(A)
Mobility formula, M. Mooney—217(A)

Electrostatics
Of the thunderstorm, A. W. Simon—754(A)

Ether-drift
Report on experiments at Cleveland, 1927, D. C. Miller—924(A)

Evaporation of water
From large bodies of water, measurements, B. and P. Richardson—755(A)

Faraday effect
Lag behind the magnetic field for various liquids, J. W. Beams, F. Allison—161
Lag behind the magnetic field, effect of wave-length, F. Allison—370(A)

Films
Of metals, x-ray analysis, K. Horovitz—352(A)
Of Ni and Fe, magnetic properties, R. L. Edwards—321

Filters for light
Liquid, for determination of color temperatures, R. Davis, K. S. Gibson—916(A)

Fine Structure
Of Balmer lines, N. A. Kent, L. B. Taylor, H. Pearson—748(A)
Of Balmer lines, W. V. Houston—749(A)
Compound interferometer for fine structure work, W. V. Houston—210(A), 478
Of He arc spectrum, W. V. Houston—749(A)
Of Hg 3650A, W. H. McCurdy—915(A)
Of Hg 2536A, Zeeman effect, W. A. MacNair—915(A)
Of infra-red absorption bands of NH_3, G. A. Stinchcomb, E. F. Barker—213(A)

Fluorescence (see also Spectra, fluorescence)
Of Cd vapor, W. A. MacNair—677
Of cod-liver oil, J. W. Woodrow, G. M. Wissink 219(A)
Of fluorescein, E. H. Kennard—466
Of iodine vapor, relation to absorption, F. W. Loomis—112
Of iodine vapor, new series, F. W. Loomis—355(A)
Of metallic vapors, by Hg arc, J. C. McLennan, I Walerstein—208(A)
Of Na vapor, R. W. Wood, E. L. Kinsey—917(A)
Of Zn induced by impact with excited Hg, J. G. Winans—213(A)
Potential of photoactive cell with fluorescent electrolytes, H. W. Russell—615(A)

Free path (see also Electron impacts)
Of K ions, as function of velocity, F. M. Durbin—215(A)

Frequency
Precise determination of, J. Tykocinski-Tykociner—366(A)
Significance in physics, W. S. Franklin—362(A)

Friction
Internal, in solids, A. L. Kimball, D. E. Lovell—616(A)

Geiger counters
Some properties of, R. D. Bennett—363(A)

Geophysics
Earth currents at Watheroo, Western Australia, and Ebro, Spain, W. J. Rooney, O. H. Gish—905(A)
Earth tides in Pasadena, W. T. Whitney—755(A)
Vertical seismometer, S. Smith—755(A)

Gravitation
Constant, redetermination, P. R. Heyl—910(A)
Constant, resonance method for determining, J. Kunz—910(A)

Hall effect
In Bi, with small magnetic fields, C. W. Heaps —332
In Te films, F. W. Warburton—905(A)

Heat
Energy of x-rays, R. Kegerreis—775
Surface heat of charging, L. Tonks, I. Langmuir —524, 614(A)
Of condensation of electrons on Mo, C. C. VanVoorhis, K. T. Compton—909(A)
Of fusion, theory, N. Rashevsky—220(A)

Heaviside layer
Absorption of radio waves in upper atmosphere, E. O. Hulburt—365(A), 706

Helium
Purification of, J. W. Cook—910(A)

Herschel-Quincke tube
Theory of, G. W. Stewart—220(A)

Humidity
Effect on heat transmission in insulating materials, L. F. Miller—370(A)
Effect on gold plated, screw-knob weights, A. T. Pienkowsky, E. S. Fowle—000(A)

Impact fluorescence (see Fluorescence)

Instruments (see also Measurements, methods)
Interferometer, compound, for fine structure work, W. V. Houston—210(A), 478
Neon glow lamp, E. Klein—610(A)
Oscillograph, Dufour, G. F. Harrington, A. M. Opsahl—364(A)
Radiometer, of molybdenite, W. W. Coblentz, C. W. Hughes—365(A): test of, W. W. Coblentz—615(A)
Shield from vibrations, R. C. Hartsough—910(A)
Spectrograph, vacuum, of large incident angle, J. B. Hoag—208(A)
Surface tension, new instrument for measuring, F. E. Poindexter—221(A)
Vacuum gauge, ionization, absolute, T. H. Johnson—610(A)
Vacuum gauage, hot wire, A. Ll. Hughes, A. M. Skellett—365(A)
Vacuum switch, H. E. Mendenhall—754(A)
Vacuum tube oscillator, theory, D. G. Bourgin —912(A)
Velocity selector, for atomic rays, J. Tykocinski-Tykociner—611(A)

Intensity relations in spectra (see also Spectra)
In bands of CN type, R. S. Mulliken—923(A)
In bands of diatomic hydrides, R. S. Mulliken —921(A)
In bands of diatomic molecules, R. S. Mulliken —211(A), 391, 637
In fundamental HCl band, D. G. Bourgin—794
Of some lines of Hg, J. Valasek—817
In spectra of isotopes of Hg and Cl, F. A. Jenkins —50

Interferometers
Applied to study of infra-red solar spectrum, H. D. Babcock—748(A)
Compound, for fine structure work, W. V. Houston—210(A), 478
Measurements on Balmer series, W. V. Houston —749(A)

Ionization by electron impact (see also Potentials, critical)
In HCl, analysis of ions formed, H. A. Barton —608(A)
In Hg vapor, probability as function of velocity, T. J. Jones —822
In Hg vapor, ultra-ionization potentials, E. O. Lawrence—609(A)
In Ga and In vapor, critical potentials, C. W. Jarvis—442

Ionization by collisions of second kind
In mixtures of H_2 and N_2 with rare gases, G. P. Harnwell—611(A), 906(A)
In rare gases, G. P. Harnwell—683
simultaneous ionization and excitation, O. S. Duffendack, H. L. Smith—914(A)

Ionization by radiation (see photoelectric effect)

Ionization gauge
Absolute vacuum gauge, T. H. Johnson—610(A)

Ionization potentials (see Potentials critical)

Ions (see also Mobility)
Dissociation of HCl by positive Na ions, H. M. Nielsen—907(A)
Excitation of Hg spectrum by positive K ion impact, E. J. Jones—611(A)
Formation of negative ions, theory, A. P. Alexievsky—752(A)
Heats of condensation of positive ions on Mo, C. C. VanVoorhis, K. T. Compton—909(A)
Nature of gaseous ions, H. A. Erikson—215(A)
Nature of gaseous ions, L. B. Loeb—752(A)
Of K, dependence of free path on velocity, F. M. Durbin—215(A)
Residual, in Hg arc, M. L. Pool—915(A)
Secondary electron emission produced by Cs ions, J. M. Hyatt—214(A)
Transformation period of initial positive air ion, L. M. Valasek—542

Ions, electrolytic
Activity of monovalent ions, H. Mueller—216(A)
Influence of, on moisture in steam, A. W. Ewell —912(A)

Isotopes
Of B, alpha bands of BO, F. A. Jenkins—921(A)
Of Hg and Cl, spectra, F. A. Jenkins—50

Kerr effect
Lag behind the magnetic field, J. W. Beams, E. O. Lawrence—903(A)

Lenses
Effect of variation from condition for achromatism, T. T. Smith—220(A)

Magnetic dipole
In Schroedinger's theory, P. S. Epstein—751(A)

Magnetic fields
In sun spots, origin of, W. F. G. Swann—905(A)
Method of measuring, J. Tykocinski-Tykociner, J. Kunz—904(A)

Magnetic properties (see also Hall effect)
Magnetic moment of atomic iodine, J. B. Taylor, T. E. Phipps—904(A)
Magnetic moment of He and H_2, I. H. Solt—904(A)
Magnetic moment of atomic hydrogen, T. E. Phipps, J. B. Taylor—218(A), 309
Magnetic moments of Fe in complex salts, L. A. Welo, O. Baudisch—612(A)
Magneto-striction in monel metal, S. R. Williams —370(A)
Of Fe, in high frequency fields, J. R. Martin—906(A)
Of evaporated Ni and Fe films, R. L. Edwards —321
Permeability of Fe and magnetite in high frequency fields, G. R. Wait—566
Susceptibilities in new quantum mechanics, J. H. VanVleck—727
Susceptibilities, principal, of crystals, I. I. Rabi —174
Susceptibilities of O_2 and NO, J. H. VanVleck—613(A)
Susceptibilities of rare earth metals, E. H. Williams—218(A)
Susceptibility of single crystal metals, C. Nusbaum—905(A)
Susceptibility of single crystal elements, C. Nusbaum—370(A)
Thermomagnetic effect in gases, N. C. Little—901(A)

Magneton numbers
In the Fe group, spectroscopic interpretation, A. Sommerfeld, O. Laporte—208(A)

Mathematics
Formal unification of grad, div, curl by operational volume, V. Karapetoff—914(A)
Log, semi-log and uniform coordinator, R. A. Castleman—910(A)
Method of least square vs. arithmetic method of determining slope of straight line, R. C. Spencer—909(A)
Variation of functions involving factorials, M. Masius—613(A)
Wave-filter determinants, analysis and application, F. D. Murnaghan, H. A. Wheeler—914(A)

Measurements, methods (see also Instruments)
Of determining sound transmission, F. R. Watson —925(A)
Of determining frequencies piezo-electrically, J. Tykocinski-Tykociner—366(A)
Of determining gravitational constant, J. Kunz —910(A)
Of drawing tube-characteristics automatically, G. C. Campbell, G. W. Willard—913(A)
Of measuring principal magnetic susceptibilities of crystals, I. I. Rabi—174
Of measuring magnetic field distribution, J. Tykocinski-Tykociner, J. Kunz—904(A)
Of measuring velocity of fluids, H. E. Hartig, H. B. Wilcox—485
Of studying short time occurrences, G. F. Harrington, A. M. Opsahl—364(A)

Mechanics, quantum
Charge density in wave mechanics, R. M. Langer —924(A)
General proof of Langevin—Debye formula and susceptibilities of O_2 and NO, J. H. VanVleck —613(A)
Influence of magnetic field on dielectric constant, L. Pauling—145
Magnetic dipole in wave mechanics, P. S. Epstein —750(A)
On conditions of validity of macro-mechanics, M. S. Vallarta—613(A)
Symmetrical top in wave mechanics, R. de L. Kronig, I. I. Rabi—262
Wave theory of electron, W. P. Allis, H. Mueller —361(A)
Wave mechanics, application to quantization of rotational energy of molecules, E. E. Witmer —362(A)

Metastable atoms
Explanation of long life, G. Breit—361(A)

Metastable atoms (cont.)
In Hg, post-arc conductivity, M. L. Pool—610(A)
In Hg, residual ions and restriking potentials, M. L. Pool—915(A)
In Ne and A, R. Rudy—359(A)

Meteorological physics
Effect of oil in storage on lightning discharge, R. W. Sorenson—754(A)
Electrostatics of thunderstorm, A. W. Simon—754(A)

Michelson-Morley experiment
Ether-drift experiments in Cleveland, 1927, D. C. Miller—924(A)

Mobility of ions
Dependence on nature of medium, H. A. Erikson—369(A)
In hydrogen gas mixtures, L. B. Loeb—751(A)
Nature of gaseous ions, H. A. Erikson—215(A)
Transformation period of initial positive ion, L. M. Valasek—542

Molecular fields (see Molecular structure)

Molecular space array
In liquid primary normal alcohols, G. W. Stewart, R. M. Morrow—919(A)

Molecular structure
Constants of AlO, moment of inertia, nuclear separation, W. C. Pomeroy—59
Electronic states and band structure in diatomic molecules III, R. S. Mulliken—391
Energy levels in CO, F. L. Mohler, P. D. Foote—141
Energy of crossed orbit model of H_2, E. Hutchisson—270
Molecular fields, D. G. Bourgin—368(A)
Of NaH, moments of inertia and nuclear separation, E. H. Johnson—85
Of NO, F. A. Jenkins, H. A. Barton, R. S. Mulliken—211(A)
Quantization of rotational energy, E. E. Witmer—362(A)
Rotational and vibrational specific heat of diatomic molecules, E. E. Witmer—918(A)
Vibrational levels in Na_2; F. W. Loomis—607(A)

Multiplets
In Cr (III) and Mn (III), R. C. Gibbs, H. E. White—917(A)
In three electron systems of first long period, R. C. Gibbs, H. E. White—655
In two-electron systems of first long period, R. C. Gibbs, H. E. White—426
In V (III), R. C. Gibbs, H. E. White—606(A)
Two-electron multiplets in first and second long periods, R. C. Gibbs, H. E. White—359(A)

Neon glow lamp
Constancy of flashing period, E. Klein—610(A)

Nodal lines
Of bells, A. T. Jones—616(A)

Nuclear structure
System for atomic nuclei, W. W. Nicholas—612(A)
Synthesis and disintegration of atoms, W. D. Harkins, H. A. Shadduck—207(A)

Optical constants
Of Cs, variation with state, J. B. Nathanson—369(A)

Optics, geometrical
Lenses, effect of variation from condition of achromatism, T. T. Smith—220(A)

Oscillators
Piezo-electric, quartz plate, theory and application, J. R. Harrington—617(A)
Piezo-electric, quartz, for determining frequencies, J. Tykocinski-Tykociner—366(A)
Piezo-electric, quartz plate, subfundamentals, J. R. Harrington—366(A)
Piezo-electric, quartz, factors influencing constancy, E. M. Terry—366(A)
Vacuum tube, shielded, for Hertzian waves, J. Tykocinski-Tykociner—217(A)
Vacuum tube, theory, D. G. Bourgin—912(A)
Vacuum tube, oscillation hysteresis, L. Taylor—617(A)

Oscillograph
Dufour, technique for short time occurrences, G. F. Harrington, A. M. Opsahl—364(A)

Passivity
Electronic theory of, W. D. Lansing—216(A)

Penetrating radiation
Variation of residual ionization with pressure at different altitudes, W. F. G. Swann—372(A)

Photoelectric conduction
In argentite, W. A. Schneider—363(A)
In crystals, significance, A. M. MacMahon—902(A)
In molybdenite, W. W. Coblentz, C. W. Hughes—365(A)
In molybdenite, tests, W. W. Coblentz—615(A)
In Se, relation to light intensity, R. J. Piersol—902(A)
In Se, influence of temperature, R. J. Piersol—362(A)
In sulphur crystals, relation to absorption, B. Kurrelmeyer—615(A)
Photoelectromotive force in Se, R. L. Hanson—924(A)

Photoelectric emission of electrons
Direction of, D. H. Loughridge—751(A)
By x-rays, explanation of Whiddington's rule, E. C. Watson—919(A)
By x-rays, relative probabilities for elements Ag to Au, F. K. Richtmyer, L. S. Taylor—353(A)
By x-rays, spatial distribution, E. C. Watson—752(A)
By x-rays, velocity and number for various angles, E. C. Watson—751(A)
From K, effect of oxygen, L. R. Koller—902(A)
From thoroughly outgassed Pt, L. A. Dubridge—451
From Na-K alloys, as function of composition, H. E. Ives, G. R. Stilwell—252, 363(A)
Instantaneity of, E. O. Lawrence, J.W. Beams—903(A)
Threshold, in Hg, changes, H. K. Dunn—693
Thresholds, periodicity with atomic number, G. B. Welsh—615(A)
Threshold, from Bi crystals, T. J. Parmley—902(A)

Photoionization of gases
Of Hg vapor, by 2537, P. D. Foote—609(A)

Photographic effects
Of slow electrons, J. E. Henderson—360(A)

Piezo-electric effects (see also Oscillators)
In crystal quartz, L. H. Dawson—216(A), 532
In crystals, shear mode of vibration, W. G. Cady—617(A)
In quartz, subfundamental vibrations, J. R. Harrison—366(A)
In quartz, theory and application, J. R. Harrison—617(A)

Polarization of radiation (see also x-rays)
Excited by electron impact, theory, J. A. Eldridge, A. Ellett, H. F. Olson—207(A)
Excited by electron impact, spinning electron, A. Ellett—207(A)
From hydrogen canal rays, K. L. Hertel—214(A), 848
Of resonance radiation in strong magnetic fields, A. Ellett—904(A)
Of Hg 2537, in magnetic field, H. F. Olson—207(A)
Of resonance radiation in Cd, W. A. MacNair—677

Potentials, critical
For Cu, excitation of soft x-rays, R. Hamer, S. Singh—901(A)
For Fe, relation between radiation and ionization potentials, O. Stuhlman—354(A)
For Fe, excitation of soft x-rays, R. Hamer, S. Singh—608(A)
In CO, for band spectra, A. B. Hepburn—212(A)
In Cu (II), Ni (I), Pd (I), A. G. Shenstone—209(A)
In Ga and In vapor, C. W. Jarvis—442
In H_2, the 29 volt critical potential, R. D. Rusk—354(A)
In Hg vapor, for spark lines, J. A. Eldridge—213(A)
In Hg vapor, ultra-ionization potentials, E. O. Lawrence—609(A)
In Hg vapor, critical restriking potentials for arc, M. L. Pool—915(A)
In In vapor, stages in excitation of spectrum, J. G. Frayne, C.W. Jarvis—673
In metal arcs, striking potentials, S. H. Anderson—750(A)
Of Li atom, second ionization potential, theory, L. Pauling—285

Proceedings of the American Physical Society
Chicago Meeting, November 26–27, 1926—204
Philadelphia Meeting, December 28–30, 1926—350
New York Meeting, February 25–26, 1927—604
Los Angeles Meeting, March 5, 1927—749
Washington Meeting, April 22–23, 1927—901

Pyrometry
Liquid filters for determination of color temperatures, R. Davis, K. S. Gibson—916(A)

Quantization
Of rotational energy in molecules by new wave mechanics, E. E. Witmer—362(A)

Quantum mechanics (see Mechanics)

Quantum of radiation
Length of, E. O. Lawrence, J. W. Beams—361(A)

Quantum theory (see also Mechanics)
Of specific heat of HCl, E. Hutchisson—360(A)

Radioactivity
Origin of actinium series, new theory, T. R. Wilkins—352(A)
Absorption of beta-rays, J. A. Gray, B. W. Sargent—351(A)
Synthesis and disintegration of atoms, W. D. Harkins, H. A. Shadduck—207(A)

Radiometers and measurements
Measurements on planet, Mars, W. W. Coblentz, C. O. Lampland—372(A)
New, selective radiometer of molybdenite, W. W. Coblentz, C. W. Hughes—365(A); tests, W. W. Coblentz—615(A)

Rectifiers
High pressure powder rectifier, J. E. Lilienfeld, C. H. Thomas—367(A)

Reflection (see X-rays)

Refraction
In moving media, N. Galli-Shohat—906(A)

Refractive index
Of gases at higher temperatures, E. W. Cheney—292
Of water, measurement, A. W. Nye—753(A)
Of water, for short electric waves, L. E. McCarty, L. T. Jones—880

Relativity
Theory of Trouton-Noble experiment, P. S. Epstein—753(A)
Report of ether-drift experiments in Cleveland, 1927, D. C. Miller—924(A)

Residual ionization
Variation with pressure at various altitudes, W. F. G. Swann—372(A)

Residual rays from crystals
Infra-red reflection spectra of some carbonates, E. K. Plyler—923(A)
Shift with pressure, F. Zwicky—579, 755(A)

Resonance
In a. c. circuits, F. H. Miller—546

Resonance potentials (see Potentials, critical)

Resonance radiation
Diffusion in Hg vapor, M. W. Zemansky—513
Polarization of Hg 2537, H. F. Olson—207(A)
Polarization in strong magnetic fields, A. Ellett—904(A)

Rijke tube
Improved form of high efficiency, R. W. Wood—373(A)

Screening constants
From optical data, O. Laporte—650

Seismometer
Vertical seismometer, S. Smith—755(A)

Shot effect
Theory, H. A. Wheeler—903(A)

Solid solutions
Of Ni-Cr and Ni-Fe, crystal structure, F. C. Blake, J. Lord, A. E. Focke—206(A)

Space charge
In triode, cause of negative resistance, L. Tonks—913(A)

Spark discharge
Study by the shadowgraph method, H. A. Zinzser—752(A)
Time of appearance and duration of spectrum lines, J. W. Beams, E. O. Lawrence—357(A)

Specific heats
Of methane, theory of, J. Kunz—220(A)
Rotational and vibrational, of diatomic gas, theory E. E. Witmer—918(A)
Of HCl, quantum theory, E. Hutchisson—360(A)

Spectra, atomic
Of B, C, N, O, F, I, S. Bowen—231
Of B, R. A. Sawyer, F. R. Smith—357(A)
Of Cr (III) and Mn (III), multiplets, R. C. Gibbs, H. E. White—917(A)
Of Cu, in hydrogen furnace, O. S. Duffendack, J. G. Black—358(A)
Of Cu, by collisions of second kind, O. S. Duffendack, H. L. Smith—914(A)
Of Cu (II), by positive neon ions, O. S. Duffendack, J. G. Black—925(A)
Of Cu and Rh, Zeeman effect, L. A. Sommer—358(A)
Of Cu (II), A. G. Shenstone—209(A), 380
Of Fe, Cr, Ti, Mg, Cu, Si, in high-current vacuum arc, A. S. King—359(A)
Of Fe, Co, Ni, absorption, W. F. Meggers—358(A)
Of Fe group, magneton numbers, A. Sommerfeld, O. Laporte—208(A)
Of first and second long period elements, two electron multiplets, H. E. White, R. C. Gibbs—359(A)
Of first long period, three-electron multiplets, R. C. Gibbs, H. E. White—655
Of first long period elements, two-electron multiplets, R. C. Gibbs, H. E. White—426
Of first period elements, relations, R. A. Millikan, I. S. Bowen—749(A)
Of Ga, In, Mn, Cr, Ni, Co, absorption in underwater sparks, A. Smith, M. Muskat—663
Of Ge, arc, C. W. Gartlein—357(A)
Of He, Stark effect, J. S. Foster—916 (A)
Of Hg and Cli, sotopes, F. A. Jenkins—50
Of Hg, infra-red, V. P. Lubovich—355(A)
Of Hg, relative intensities, J. Valasek—817
Of ionized P, I. S. Bowen—749(A), 510
Of Na, K, Cs, Mg, Cd, Zn, Hg, Tl, by atomic hydrogen, F. L. Mohler—354(A), 419
Of Ne, Stark effect, J. S. Foster, W. Rowles—925(A)
Of Ni, spark, A. G. Shenstone—917(A)
Of oxygen, ultra-violet, J. J. Hopfield—923(A)
Of Sb, absorption, R. V. Zumstein—209(A)
Of Sc, arc and spark, analysis, H. N. Russel, W. F. Meggers—606(A)

Spectra, atomic (cont.)
Of stripped atoms, relations, R. C. Gibbs, H. E. White—359(A)
Of V (III), multiplets, R. C. Gibbs, H. E. White—606(A)

Spectra, auroral
Note on the auroral green line 5577, D. A. Keys—209(A)

Spectra, excitation of
Of CO_2, by electron impact, G. W. Fox, O. S. Duffendack, E. F. Barker—921(A)
Of Cu and CuH, in hydrogen furnace, O. S. Duffendack, J. G. Black—358(A)
Of Cu, by collisions of second kind, O. S. Duffendack, H L. Smith—914(A)
Of Cu (II), by positive neon ions, O. S. Duffendack, J. G. Black—925(A)
Of Hg, spark lines, critical potentials, J. A. Eldridge—213(A)
Of Hg, by positive ion impact, E. J. Jones—611(A)
Of In, by electron impact, J. G. Frayne, C. W. Jarvis—357(A), 673
Of N, by electron impact in mixture with He, R. A. Wolfe, O. S. Duffendack—209(A)
Of Na, K, Cs, Mg, Cd, Zn, Hg, Tl, by atomic hydrogen, F. L. Mohler—354(A), 419

Spectra, fluorescent
Of iodine, correlation with absorption, R. W. Loomis—112
Of iodine, new series, F. W. Loomis—355(A)
Of Na vapor, R. W. Wood, E. L. Kinsey—917(A)
Of S, Se, Te, Bi vapors excited by Hg arc, J. C. McLennan, I. Walerstein—208(A)

Spectra, molecular
Of AgH, AlH, ZnH, MgH, Zeeman effect, W. W. Watson, B. Perkins—921(A)
Of AlO, quantum analysis, W. C. Pomeroy—59
Of benzene derivatives, shift of absorption bands, J. Barnes—922(A)
Of BO, structure and isotope effect in alpha bands, F. A. Jenkins—921(A)
Of CaH, E. Hulthèn—97
Of C_2H_2, C_2H_4, C_2H_6, infra-red absorption, C. F. Meyer, A. Levin—923(A)
Of CH_4, new infra-red absorption bands, J. W. Ellis—751(A)
Of CO, ultra-violet emission and absorption, J. J. Hopfield, R. T. Birge—922(A)
Of CO, A. B. Hepburn—212(A)
Of CO_2, G. W. Fox, O. S. Duffendack, E. F. Barker—921(A)
Of CuH, O. S. Duffendack, J. G. Black—358(A)
Of fluorine, continuous emission and absorption, H. G. Gale, G. S. Monk—211(A)
Of hydrocarbons, F. C. McDonald—212(A)
Of iodine, absorption, F. W. Loomis—112
Of MgH, rotational terms, W. W. Watson, P. Rudnick—413
Of Na, vibrational levels in blue-green bands, F. W. Loomis—607(A)
Of Na and K, absorption bands, W. R. Fredrickson, W. W. Watson, J. Rinker—917(A)
Of NaH, many-lined spectrum, E. H. Johnson—85
Of NH_3, infra-red bands, fine structure, G. A. Stinchcomb, E. F.Barker—213(A)
Of NH_3, infra-red, W. F. Colby, E. F. Barker—923(A)
Of N_2, air, C_2H_2, CO, extreme ultra-violet absorption, J. J. Hopfield—356(A)
Of N_2, ultra-violet, R. T. Birge, J. J. Hopfield—356(A)
Of NO, beta bands, F. A. Jenkins, H. A. Barton, R. S. Mulliken—211(A)
Of O_2 in ultra-violet, V. Ellsworth, J. J. Hopfield—79
Of Ti, quantum analysis, R. T. Birge, A. Christy—212(A)

Stark effect
In He arc spectrum, theory, J. S. Foster—916(A)
In Ne, J. S. Foster, J. W. Rowles—925(A)

Sun spots
Origin of magnetic fields of, W. F. G. Swann—905(A)

Surface tension
New instrument for measuring, F. E. Poindexter—221(A)
Of molten copper, as function of temperature, E. E. Libman—911(A)
Of oils, variation with temperature, G. Winchester—911(A)

Surface layers
On W, produced by active nitrogen, C. Kenty, L. A. Turner—914(A)

Susceptibility (see Magnetic properties)

Temperature
Distribution along a wire, V. Bush, K. E. Gould—337
Variations in wires heated by a. c., L. Smede—614(A)

Thermal conductivity
Of fused quartz as function of temperature, H. E. Seemann—616(A)
Of insulating materials, affected by humidity, L. F. Miller—370(A)

Thermal expansion
Of Be, P. Hidnert, W. T. Sweeney—616(A)
Of graphite, P. Hidnert, W. T. Sweeney—371(A)
Of nickel steels, P. Hidnert, W. T. Sweeney—911 (A)
Of quartz, E. W. Cheney—292

Thermionic emission of electrons
Effect of surface layers produced by active nitrogen, C. Kenty, L. A. Turner—914(A)
Emission and diffusion constants for tungsten containing various oxides, S. Dushman, D. Dennison, N. B. Reynolds—903(A)
Equations for, W. R. Ham—607(A)
Factors influencing, A. K. Brewer—752(A)
From thoriated tungsten, S. Dushman, J. W. Ewald—857(A)
Interpretation of data, W. R. Ham—364(A)
Shot effect, theory, H. A. Wheeler—903(A)
Space charge as cause of negative resistance, L. Tonks—913(A)
Surface heat of charging, L. Tonks, I. Langmuir—524, 614(A)

Thermodynamics
Absolute zero of entropy and energy, R. D. Kleeman—369(A)
Properties of substances in condensed state at absolute zero, R. D. Kleeman—614(A)
Reversible mixing of substance in condensed state at absolute zero, R. D. Kleeman—912(A)

Thermoelectric effects
In single crystal Zn, E. G. Linder—221(A), 554

Thermomagnetic effects
In gases, N. C. Little—901(A)

Trouton-Noble experiment
Theory of, P. S. Epstein—753(A)

Ultrasonic rays
Physical and biological effect, R. W. Wood—373 (A)

Undulatory mechanics (see Mechanics)

Vacuum tubes (see also Thermionic emission)
Device to draw characteristic curves automatically, G. C. Campbell, G. W. Willard—913(A)
Oscillator, theory, D. G. Bourgin—912(A)
Oscillation, hysteresis, L. Taylor—617(A)
Space charge as cause of negative resistance in, L. Tonks—913(A)

Vacuum switch
New type, H. E. Mendenhall—754(A)

Valence
Effect on x-ray absorption, W. B. Morehouse—924(A)

Velocity selector
For atomic rays, J. Tykocinski-Tykociner—611 (A)

Vibrations
Continuous motion produced by, W. B. Morton, A. McKinstry—192
Shielding from, R. C. Hartsough—910(A)

Viscosity
Internal, in solids, A. L. Kimball, D. E. Lovell—616(A)

Wave mechanics (see Mechanics)

Weights
Variation with humidity of gold-plated, screw-knob, A. T. Pienkowsky, E. S. Fowle—910(A)

Wireless (see Electrical oscillations)
Work function (see Thermionic emission)

X-rays absorption
Formulas, S. J. M. Allen—918(A)
L absorption edges, Sn to Ru, G. D. Van Dyke, G. A. Lindsay—205(A)
M series absorption of Os, Ir, Pt, R. A. Rogers—205(A)
Of celluloid, air, H_2, for soft x-rays, E. R. Laird—41
Relation to valence, W. B. Morehouse—924(A)
Test of theories, F. K. Richtmyer, L. S. Taylor—606(A)

X-ray analysis (see Crystal structure)

X-rays, characteristic
Possible dependence on temperature, J. H. Purks, C. M. Slack—352(A)

X-rays, chemical effects
Coloration of kunzite and hiddenite, P. L. Bayley—353(A)
Combination of H_2 and O_2, R. D. Rusk—907(A)

X-rays, diffraction
By ruled gratings, F. L. Hunt—919(A)
Measurements on compounds in Portland cement, E. A. Harrington—353(A)

X-rays, general radiation
From very thin target, W. Duane—606(A)

X-rays, energy
For therapeutic use, H. Clark—605(A)
Heat energy, R. Kegerreis—775
Of soft x-rays, 40–610 v., E. R. Laird—41

X-ray isochromats
Of Cu, taken in different directions, W. W. Nicholas—619

X-rays, polarization
Polarization angle, C. S. Barrett, J. A. Bearden—352(A)
Polarization factor in reflection, P. Kirkpatrick—632

X-rays, reflection and scattering
By crystals, Compton effect, G. E. M. Jauncey——206(A)
By crystals, theory, S. K. Allison—375, 749(A)
From NaCl and Al, electron distribution, J. A. Bearden—20
From NaCl, Li F, NaF, CaF_2, electron distribution, R. J. Havighurst—1
Gyromagnetic electron theory of Compton effect, L. V. King—919(A)
Intensity, Compton effect, G. E. M. Jauncey—605(A)
Intensity, theory, G. E. M. Jauncey—757
Of soft x-rays, E. R. Laird—605(A)
Polarization factor in reflection, P. Kirkpatrick—632

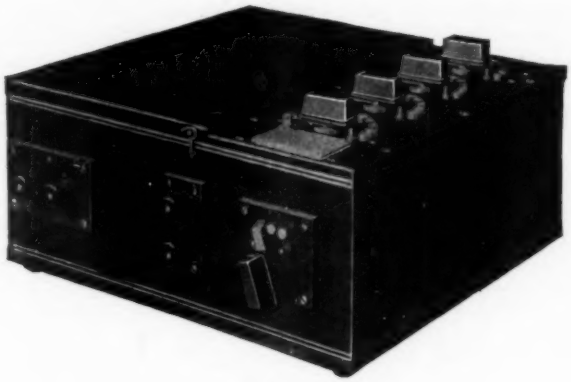
X-ray refraction
By total reflection, R. L. Doan—205(A)

X-rays, soft
Absorption, E. R. Laird—41
Diffraction, by grating, F. L. Hunt—919(A)
From Cu, critical potentials, R. Hamer, S. Singh—901(A)
From Fe, critical potentials, R. Hamer, S. Singh—608(A)
O and N levels of tungsten, H. E. Krefft—902(A)
Reflection of, E. R. Laird—605(A)

X-rays, photoelectric effect
Explanation of Whiddington's rule, E. C. Watson—919(A)
Probabilities of photo-emission, Ag to Au, F. K. Richtmyer, L. S. Taylor—353(A)
Recoil electrons from Al, A. A. Bless—918(A)
Spatial distribution of photoelectrons, E. C. Watson—752(A)
Velocity and number of photoelectrons as function of angle, E. C. Watson—751(A)

X-rays, therapeutic
Measurement of x-rays used for therapy, H. Clarke—605(A)

Zeeman effect
In AgH, AlH, ZnH, MgH bands, W. W. Watson, B. Perkins—921(A)
Of arc spectra of Cu and Rh, L. A. Sommer—358(A)
Of fine structure components of 2536 of Hg, W. A. MacNair—915(A)



Capacity Bridge

Type 216

The Type 216 capacity bridge is designed for the accurate measurement of capacitance and equivalent series resistance. Thorough shielding and non-reactive ratio arms insure a high degree of precision in measurement of small capacitances.

It is particularly adapted to the study of dielectric phenomena.

Price $150.00

Bulletin No. 412

GENERAL RADIO COMPANY
30 STATE STREET
CAMBRIDGE, MASSACHUSETTS

INFORMATION FOR CONTRIBUTORS TO THE PHYSICAL REVIEW

Purpose of the Review is to publish articles that add to our knowledge of experimental or theoretical physics.

Articles which have not previously been published may be submitted by any physicist whether American or not. Each manuscript will be acknowledged by the Managing Editor as soon as received. An article to be considered must be in English and in a form ready for publication; it must be provided with a preliminary abstract prepared in accordance with the directions given on a following page. Carelessly written articles and figures not carefully drawn will be returned for revision. All manuscripts should be typed double space and symbols written in with great care so as to be quite clear to the printer.

Suggestions as to Contents. On account of the high cost of printing, brevity is of great practical importance. Historical summaries of previous results and also discussions which consider various possible explanations without leading to definite conclusions should be made very brief, except in special cases. The greater part of the paper should be devoted to the actual new results and to a concise presentation of the conclusions to which they lead. Attention should be directed to the more accurate and more conclusive experiments, omitting any which add nothing. The amount of detail included should be governed somewhat by the importance of the results and their interest to physicists.

Suggestions as to form. Clearness is of great importance. Pains should be taken to insure that the order and form of presentation are such as to enable the reader to grasp the new information as easily and quickly as possible. In general the order should be: Statement of the problem and of the purpose, scope and general method of the investigation, followed by a description of the apparatus, experiments and results in such order as to bring out clearly the evidence for the main conclusions, the paper ending with perhaps a brief discussion of the significance and bearing of the results on other problems. Avoid the historical or laboratory note-book style; use rather the text-book or lecture style. Footnotes should be numbered consecutively and each reference should contain author's name.

Abbreviations. Omit periods after such symbols for units as the following: cm, mm, kv, lb, A, °C; also after I, II, . . . and percent, and after headings in columns in Tables. Write a.c., e.m.f., abscissas, disk, in vacuum, wave-length, x-rays, per-cent. Refer to figures as Fig. 1, Figs. 3 and 4; and to equations as: Eq. (5); Eqs. (7) and (8). Number equations on the right.

Mathematics. Indicate division by a slant line where possible. Avoid unusual symbols, symbols with rules over them, cumbersome fractions.

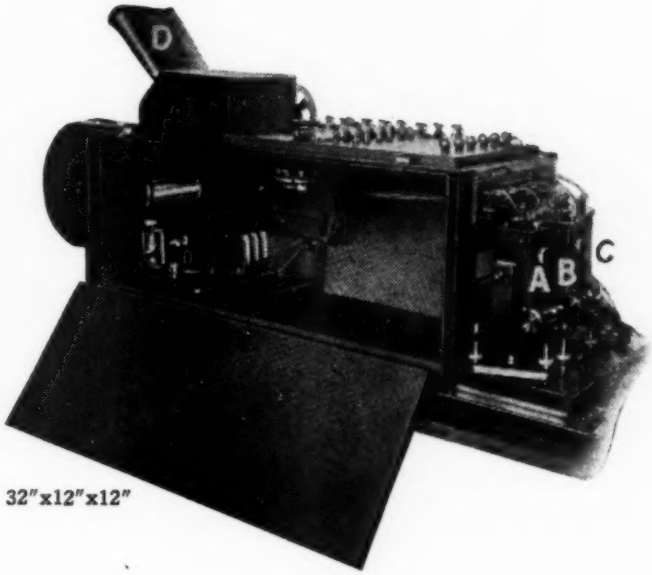
Figures or illustrations. Use only jet black ink, on white or on blue-lined cloth or paper. Tracing cloth is especially suitable. Curves plotted or traced on such cloth or paper may have co-ordinates ruled in black at desired intervals, say every centimeter or inch, as blue lines are not reproduced photographically. *Colors other than blue and black should be avoided.* Indicate observed points on all plots. Arrange material in each figure compactly. It is well when possible, to make the longer dimension horizontal, as larger reproduction can then be permitted; if vertical figures are necessary, space may be saved by making two of the same height, and putting them side by side. *All lettering should be at least* $\frac{3}{16}$*" high* for an 8"×10" figure, so as to be legible after reduction. Lettering left in pencil will be inked in by a draftsman in this office. In general each figure and table should have a caption, describing it briefly. Reduce the number of tables and figures to the necessary minimum.

Proofs. Galley proof of each article is sent directly from the publishers to the author and should be corrected with great care so as to eliminate all errors, as page proof cannot always be submitted. Only necessary changes should be made; extensive additions will mean the delay of a month in publication. All corrected proof should be sent promptly with the manuscript to THE PHYSICAL REVIEW, 1500 University Ave., S. E., University of Minnesota, Minneapolis.

Permission to republish any article is given, if proper acknowledgment is made.

Reprints ordered on the proper form with the return of the galley proof, will be furnished by the printer according to the prices given on the form.

CAMBRIDGE INSTRUMENTS



32″x12″x12″

Duddell Oscillographs

Duddell Oscillographs are deadbeat; they have practically no self-inductance and capacity; are highly sensitive, and have short periodic time compared with the periods of the wave forms being recorded.

Three types are offered: Type 1 for recording rapidly varying phenomena for use upon high frequency circuits up to 550 volts; Type 2 for circuits up to 100,000 volts; and Type 4 for demonstration purposes. Special outfits are furnished incorporating any desired number of vibrators.

Type 2 Oscillograph illustrated above, is designed for commercial use. It is portable, robust and easy to operate. Simultaneous records may be taken with three vibrators (A, B and C). These vibrators are small in size, are interchangeable, and may be used in any combination of the electrostatic and the electromagnetic types. Only one camera and one source of light are required and the wave form may be observed (through aperture D) up to the moment of exposure.

Send for List IV-P

Temperature Measuring & Controlling Instruments
Engineering Instruments
D. C. Electrical Instruments

CAMBRIDGE INSTRUMENT Co INC

FACTORY OSSINING-ON-HUDSON NEW YORK

SALES OFFICE & SHOWROOM GRAND CENTRAL TERMINAL NEW YORK CITY

A. C. Electrical Instruments
Physiological Instruments
Special Instruments

Address inquiries to sales office

No. 1684

New Features of the

Cavendish Form

Mechanical Equivalent of Heat Apparatus

Greater Accuracy ***More Uniform Results***

The new method of construction provides for the force opposing friction being applied as a couple and measured by a spring balance.

By means of the couple it is possible to get a more constant reading of the force and thus more consistent and uniform results.

With the new arrangement the difficulty of the weights climbing or dropping to the floor is completely eliminated.

Careful designing and workmanship insure accurate results.

No. 1684 Mechanical Equivalent of Heat Apparatus $65.00

TYPICAL RESULTS OF TEST
For Mechanical Equivalent of Heat

Diam. of wheel	14.8 cm.
Water equivalent of both cones	18.28 g.
Room temp.	25.25° C.
Initial temp.	19° C.
Final temp.	31.35
Rise in temp.	12.35° C.
Counter reading, first	87,965
Counter reading, second	90,449
Number of revolutions	2,484
Weight of water in cone	38.8 g.
Pull of spring balance	259 g.

$$H=\frac{14.8\ \pi \cdot 259 \cdot 2484}{(38.8+18.28)\ 12.35}=42{,}440 \text{ gram-cm.}$$

Approved value 42,700 gram-cm.
Error=.6%

Do you have a copy of our new Catalog "G"? If not, a copy will be sent you upon request, giving your official position.

Pacific Coast Distributors

BRAUN-KNECHT-HEIMANN COMPANY
576-584 Mission Street
San Francisco, Calif.

BRAUN CORPORATION
363 New High Street
Los Angeles, Calif.

A Sign of Quality QUALITY WELCH SERVICE *A Mark of Service*

W. M. Welch Scientific Company

Scientific Department of the W. M. Welch Manufacturing Company

1516 Orleans St., Manufacturers, Importers and Exporters of Scientific Apparatus and School Supplies **Chicago, Ill., U.S.A.**

PHYSICAL REVIEW

PREPARATION OF PRELIMINARY ABSTRACTS

An article will not be accepted for publication in THE PHYSICAL REVIEW unless the manuscript is accompanied by an adequate abstract for publication at the beginning of the article. This abstract is intended to aid the reader by furnishing an index and a brief summary of the contents of the article. Besides serving these purposes it should also be suitable for reproduction in abstract journals so as to make it unnecessary for the editors of these journals to have another abstract prepared.

As an index it should be complete; all the subjects, major and minor, concerning which new information is presented, should each be given, with sufficient precision so that any reader can tell from the abstract whether the article contains anything of interest to him. The subject indexes of abstract journals are fundamental in reference work. These indexes are prepared exclusively from the abstracts and whatever is omitted from the abstracts cannot be included in the index and may thus be lost. The writer of an abstract should therefore feel himself under an important obligation to his scientific colleagues to make sure that the abstract is accurate and complete, at least as an index.

As a summary the abstract should give briefly the conclusions of the article, important advances in experimental technique and theory, and all numerical results of general interest that may be conveniently given including all that might belong in a hand book and table of constants. It should give all the information that readers who are not specialists in the particular field involved might desire to know about the article thus saving them the time and trouble in referring to the article itself. Experience has shown that in general the length of the abstract should be from four to eight percent of the length of the article.

THE PHYSICAL REVIEW 1923-1925 contains many examples of adequate abstracts. Most of these contain paragraph titles and subtitles which indicate the subjects concerning which new information is given and it is requested that authors include such subtitles when all the information contained in the article does not refer to the subject indicated by the title of the article. Such subtitles may be frequently avoided by rewording the title so as to make it more precise.

NUMERICAL DOCUMENTATION

Biologists, Chemists, Physical Chemists, Physicists, Engineers, etc., etc.

WHY WASTE YOUR TIME

in searching the Literature to find the Constant or the numerical data that you require?

Since 1910 the Collaborators of the Committee have done this work for you in publications that have appeared all over the world.

The results of this work have been classified and published in

Annual Tables of Constants and Numerical Data

published under the patronage of the International Research Council and of the International Union of Pure and Applied Chemistry.

IF YOU ALREADY KNOW the Annual Tables, make them known to your friends; you will render them a great service.

IF YOU DO NOT KNOW THEM, write at once to **M. C. MARIE, General Secretary of the International Committee, 9 rue de Bagneux, PARIS (6e).**

VOLUMES PUBLISHED

Volume I (data for 1910)
Volume II (data for 1911)
Volume III (data for 1912)

Volumes I, II, III, are sold only with volumes IV, and V.

Cloth Bound

Volume IV (data for 1913-1916).....$25
Volume V (data for 1917-1922).....$25
Price of a complete set
(Volume I, II, III, IV, V).....$71

IN THE PRESS:

(Volume VI (data for 1923-1924)

Closing date of the subscription June 30, 1927

Subscription Price: (Bound copies)
Ordinary subscribers $20
Members of Scientific Societies and Subscribers to The International Critical Tables $15

From July 1, 1927, onwards, the price of Volume VI will be increased to.....$30

Subscriptions Should Be Sent with the Remittance

To McGRAW HILL BOOK CO., Inc., 370 Seventh Avenue, New York, U. S. A.

The Secrétariat of the Committee (9,rue de Bagneux, Paris) sends free of charge specimen pages taken from the following chapters: *Spectroscopy, Electricity, Magnetism, Electrochemistry, Radioactivity, Crystallography, Minerology, Biology, Engineering, Metallurgy, Colloids.*

Our regular plates printed on different sized paper

Just a few days ago one of our customers wanted a size to be cut from a larger size and trimmed without margin. Some want margins on the paper different from our stock. In lots of five hundred sheets or more we will make the changes without much extra cost.

CORNELL CO-OPERATIVE SOCIETY

BARNES HALL **ITHACA, N. Y.**

Western Electric
Vacuum Thermocouples

Interior View of Container Showing a Vacuum Thermocouple

Western Electric Vacuum Thermocouples provide an accurate means for measuring the values of feeble alternating currents. This new apparatus is of great value to research organizations and scientific laboratories. It is essentially a hot wire instrument enclosed in an evacuated container.

Vacuum Thermocouples are made in three standard types with various characteristics. With the proper type and a suitable galvanometer any current from .0005 ampere to 1.0 ampere may be measured with an accuracy of plus or minus 1%.

For further information write for Bulletin T-761.

GraybaR
ELECTRIC COMPANY
SUCCESSOR TO Western Electric SUPPLY DEPARTMENT

Scientific Equipment Division

Lexington Ave. and 43rd St. . . . . New York, N. Y.
30 North Michigan Boulevard . . . . . Chicago, Ill.
910 Cherry Street . . . . . Philadelphia, Pa.

TOROIDAL INDUCTANCE STANDARDS

These toroidal inductance standards have the distinct advantage that they are practically immune from stray field errors. The toroidal windings also prevent setting up external fields which might affect other circuits or apparatus.

The windings of these inductance standards are made up of wire having such small cross-section that there is no appreciable increase in resistance when used at audio frequencies.

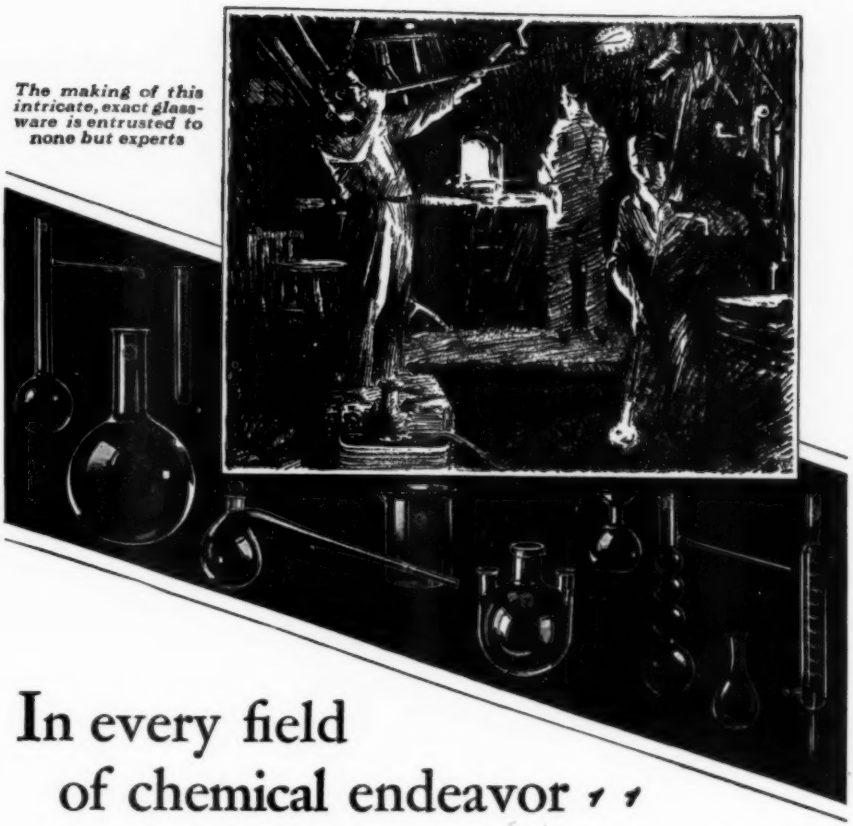
1530	**1-Millihenry Standard of Self Inductance** Current capacity 1 amp. continuously—accuracy .25%.	$30.00
1531	**10-Millihenry Standard of Self Inductance** Current capacity .5 amp. continuously—accuracy .25%.	30.00
1532	**100-Millihenry Standard of Self Inductance** Current capacity .15 amp. continuously—accuracy .25%.	30.00
1533	**1000-Millihenry Standard of Self Inductance** Current capacity .05 amp. continuously—accuracy .25%.	30.00
1540	**50-Millihenry Standard of Mutual Inductance** Current capacity .15 amp. continuously—accuracy .25%. Construction same as illustration except that 4 binding posts are provided.	40.00

Described in Catalog P-10

LEEDS & NORTHRUP COMPANY
4901 STENTON AVENUE, PHILADELPHIA

LEEDS & NORTHRUP

Galvanometers
Potentiometers
Bridges and Resistances
Condensers and Inductances
Testing Sets
Recording and Controlling Pyrometers
Pumps and Homo
Electric Heat Treating Furnaces
Instruments for Measuring and Controlling Conductivity of Electrolytes and Hydrogen Ion Concentrations



The making of this intricate, exact glassware is entrusted to none but experts

In every field of chemical endeavor

this trade-mark is the recognized standard

EXPERIENCED chemists all over the world specify *PYREX laboratory glassware. They know that back of the PYREX trade-mark stand years of research, highly specialized experience, carefully trained craftsmen, and rigid inspection. They know that each piece of PYREX equipment is uniformly dependable—and durable to the highest possible degree.

CORNING GLASS WORKS
Laboratory Glassware Division, Corning, New York
New York Office: 501 Fifth Avenue
Largest Makers of Technical Glassware in the World

**Trade-mark Reg. U. S. Pat. Off.*

The trade-mark PYREX designates a product of Corning Glass Works. It is synonymous with highest quality in materials and workmanship.

THE BURT-CELL

A Photo-Electric Cell

WITHOUT FATIGUE. It will record direct sunlight (10,000 foot candles) all day and immediately afterward accurately measure the light from a flashlight bulb at one meter.

HIGHLY SENSITIVE, giving one microampere per 100 foot candles.

LINEAR. By careful measurement it is found to have accurately a linear current light relation from 1/10 to 1000 foot candles.

PERFECTLY STABLE. High voltage and extreme light over long periods will not impair its accuracy, even temporarily.

ABSOLUTELY REPRODUCIBLE from day to day.

INSTANTANEOUS IN RESPONSE. Each cell is tested by an expert and shipped with a standardized calibration. The variation from cell to cell is extremely small.

THE BURT-CELL is a new photo-cell made by an entirely different process and should not be confused with any other photo-electric cell.

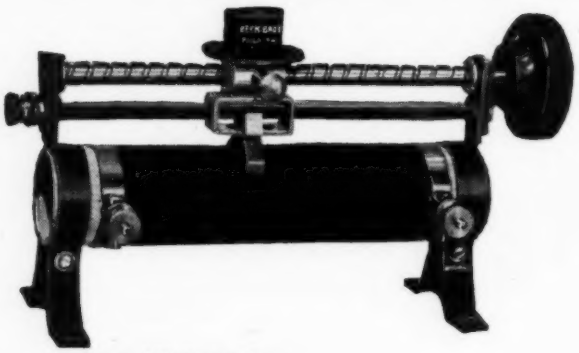
Write for bulletin number 271

Scientific Instruments

DR. R. C. BURT
327 South Michigan Ave.
PASADENA, CALIFORNIA
Cable address: *"Burt Pasadena"*

Research Fellow California Institute of Technology

BECBRO
Laboratory Rheostats



Screw Adjustment Type

"BECBRO" Rheostats carried in stock include numerous ratings.

Included in the stock sizes are tubular types of length 20"; 16"; 8"; the resistance element being Wire or Ribbon.

Each tube has a slider adjustment which varies the resistance by very small steps from Zero to total value of the unit.

The approximate total resistance of these stock rheostats vary from 0.3 ohm to 30,000 ohms per unit, and have corresponding current capacities of 25 amperes down to 0.1 ampere.

Rheostats of more or less special construction include the Single Tube equipped with two rods and two sliders; Single and Double Tube equipped with Screw Adjustment (see cut); Double and Triple Tubes mounted as a Unit; Non-Inductive Wound Tubular and Stone Types.

"BECBRO" Carbon Compression Rheostats with corresponding Normal Ratings of 250; 1000; 1500; 3000 Watts.

Write for Catalog P-20

BECK BROS.

3640-42 North Second Street — Philadelphia, Pa.

QUALITY

Modern requirements for testing equipment have determined the design and construction of G-E Portable Instruments.

They are of quick period and inherently immune from the effects of adjacent electric circuits. The windings are of special alloy to provide unchanging resistance values and consequent freedom from errors caused by thermal and parasitical voltages or temperature changes.

Such features contribute to the high and sustained accuracy which has characterized G-E Portable Instruments for more than a generation.

GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY, SCHENECTADY, N. Y.

G-E Portable Instruments

A-c. (*Type P-3*)	D-c. (*Type DP-2*)
Voltmeters	Voltmeters
Ammeters	Ammeters
Milliammeters	Millivoltmeters
Wattmeters	Milliammeters
Power Factor Meters	Microammeters
Frequency Meters	Thermal-Ammeters
	Ohmmeters

The above instruments can be furnished with standard or special ratings to conform with every requirement. All scales are hand calibrated and marked to fit the characteristics of the individual instrument—a final operation of extreme importance in co-ordination of electrical and mechanical design.

Special Instruments

General Electric Engineers are constantly in search of new methods for the indication of electrical measurements. Among the most recent developments is a thermionic microammeter that will indicate a current change so small as one ten-billionth of an ampere.

There are also thermal and suspended-armature types, of high sensitivity, which have proved to be invaluable for laboratory use.

Whatever your problems of electrical measurement, G-E Engineers welcome the opportunity to be of assistance in their solution. Detailed information will be gladly supplied from the nearest G-E Sales Office.

610-12

GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY, SCHENECTADY, N. Y.

Siemens & Halske

Precision Millivolt—

***and* Voltmeter**

is used largely by Physicists, Electrical, and Electrochemical Engineers in Research Laboratories. It is different in design, construction and characteristics from any other d.c. measuring instrument made.

As a Millivoltmeter the range is 0 to 45 mv., with resistance of 10 ohms; and as a Voltmeter the range is 0 to 3 volts, with a resistance of 1000 ohms. **All ranges are compensated for temperature changes; the instrument is accurate and it holds its calibration.**

Illustrated Catalog 1015-R will be sent on request.

Write for copy.

JAMES G. BIDDLE
Scientific Instruments
1211-13 Arch Street, PHILADELPHIA

Cat. No.	*Description*	*Price*
560001	Precision Millivolt and Voltmeter for 45 millivolts and 3 volts, 150 scale divisions. Complete with carrying case	$74.25
560006	Precision Combined Manganin Shunt for .015, .03 and .075 amperes	$20.25
560007	Ditto, for .15, .3 and .75 amperes	$13.50
560008	Ditto, for 1.5, .3 and 7.5 amperes	$14.40
560009	Ditto, for 15 and 30 amperes	$15.30
560010	Precision Manganin Shunt for 75 amperes	$ 9.00
560024	Combined Multiplier for 15, 150, 300 and 750 volts	$36.00

The above prices are net f.o.b. Philadelphia

Describing Taylor Process Fine Wires

THE TAYLOR PROCESS for making wires from substances which lack ductility, was described in part in the Physical Review for May, 1924, pages 655-660. In a general way, the process consists in melting, or almost melting, the material in a glass or quartz tube and drawing down to the required size. The article gave the method for obtaining wires from materials like Bismuth only. But the process has been so developed since that many other substances can be drawn into wire by the Taylor Process. The elements or alloys being drawn in glass or quartz are in a very pure state. Lengths of more than a few feet cannot be obtained. The wires may be had with or without the glass insulation.

We make Taylor Process wire of Pt, Pd, Rh, Au, Ag, Cu, Fe, Co, Zn, Cd, Pb, Sb, Bi, Sn, Se, Te, Ti, Ga, and In, Constantan, Bi-Sn, Cd-Sb (alloy where large E.M.F. is desired) and many other alloys. Our wires are packed in containers holding one foot. With few exceptions, the sizes are from one mm to one micron. We manufacture too, fine wire by the Wollaston Method, by extrusion and by bare drawing.

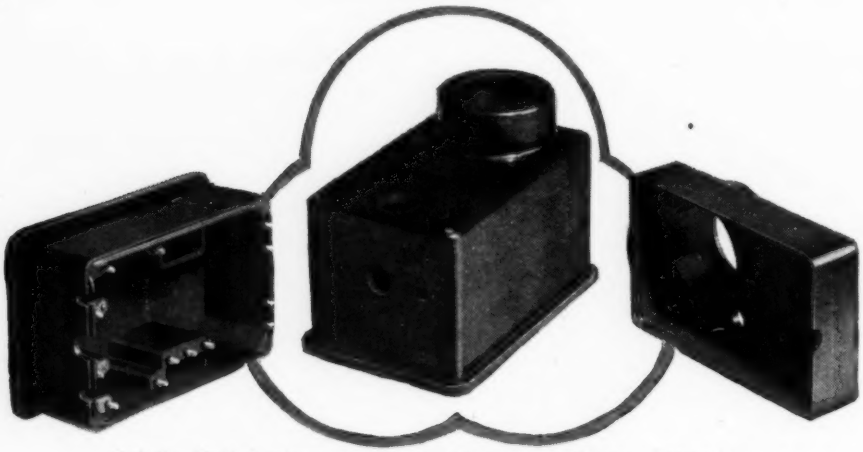
Whenever you may need wire or sheet from unusual materials or in unusual sizes, write us. Very probably we can supply you.

BAKER & CO., INC.
54 Austin St., Newark, N. J.

30 Church St.
New York

760 Market St.
San Francisco

5 So. Wabash Ave.
Chicago



Bakelite Molded relay case made by Central Scientific Co., Chicago, Ill.

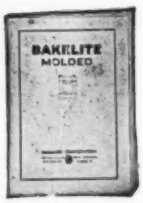
Three Bakelite Molded cases
produced at the cost of one of metal

WHEN the relay case pictured above was formed of metal, expensive machining and finishing were required. Both of these operations were eliminated through the use of Bakelite Molded and the cost of the case reduced 62½ per cent. In the cost is figured the die charge.

The over-all dimensions of this case when closed are 3¼ in. x 6⅛ in. x 4¼ in., and each of its two parts is formed in a single Bakelite molding operation. Nine metal inserts are solidly embedded and relief lettering formed during the molding process. The appearance was improved because of the high lustre and rich color of Bakelite.

Many manufacturers have found that the use of Bakelite Molded reduces the final cost through reducing, or eliminating, the number of machining, finishing and assembly operations required when other materials are used. Similar economies may be possible in your own work.

We invite those who are interested in lowering the cost of production, or in improving quality to enlist the cooperation of our engineers and research laboratories. In this connection our Booklet No. 12, "Bakelite Molded," would interest you and a copy will be mailed promptly on receipt of your request.



BAKELITE CORPORATION

247 Park Ave., New York, N. Y., Chicago Office: 635 W. 22nd St.

BAKELITE CORP. OF CANADA, LTD., 163 Dufferin Street, Toronto, Ont.

BAKELITE

REGISTERED U. S. PAT. OFF.

THE MATERIAL OF A THOUSAND USES

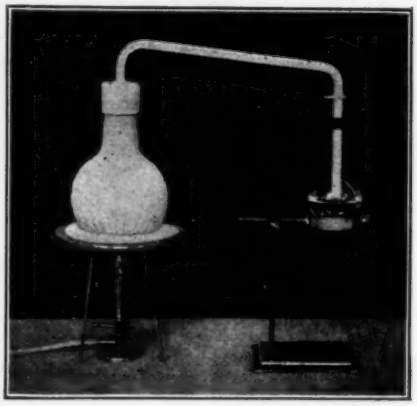
"The registered Trade Mark and Symbol shown above may be used only on products made from materials manufactured by Bakelite Corporation. Under the capital "B" in the numerical sign for infinity, or unlimited quantity. It symbolizes the infinite number of present and future uses of Bakelite Corporation's products."

Back Numbers Wanted of the
PHYSICAL REVIEW

We will pay $1.50 each for copies of the January, February, April and May issues of Volume 7, 1916.

Send to the Physical Review, 1500 University Ave. S. E.
Minneapolis, Minn.

Fused Pure Silica
Vitreosil



Distilling Apparatus *for* Conductivity Water

(As designed by Professor James Kendall)

The most delicate electrical and chemical tests point to the complete insolubility of vitreosil in distilled water, no other material known being its equal in resistance to the solvent action of pure water.

Illustrated above is a suggested method for erecting this apparatus comprising a three liter opaque still, 500 cc transparent receiving flask, and opaque connecting bend.

Price Complete **$67.50**
(Vitreosil Parts Only)

Write for Particulars

Obtainable through dealers or direct from

The Thermal Syndicate, Ltd.

1726 Atlantic Avenue Brooklyn, New York

PURE FUSED SILICA VITREOSIL

QUARTZ SPECTROGRAPH

Gaertner Improved Model

L 250 QUARTZ SPECTROGRAPH. This instrument is so designed as to photograph the emission and absorption spectra in the visible and ultra violet regions from 800 Mu Mu to 185 Mu Mu.

Collimator and the camera lenses are made of quartz, 25mm. aperture. The prism is of Cornu type (built up of two thirty degree prisms of left and right handed quartz, with faces in optical contact) and its faces are 20 mm high and 30 mm long. In this new model, the plate holder, the slide and the camera box are made of metal throughout. The plate holder takes a standard size plate, namely, 3-¼ by 4-¼ inches and may be readily shifted vertically by rack and pinion motion for the successive exposures of spectra. A millimeter scale is attached to the slide serving to indicate the position of the plate. A shutter on the slit permits the taking of the comparison spectra in juxtaposition. The necessary adjustments for focusing the lenses and tilting the plate are provided. The bellows on the camera are of black velvet, which is light tight and will not deteriorate with use..... $285.00

L 250a Wavelength Scale. (Interchangeable). Accurate wavelength scales are prepared for each instrument. These scales are accurately divided on glass and etched. By laying it on the spectrogram the wavelength may be read off directly..... $ 40.00

Immediate shipment from stock.

The
GAERTNER SCIENTIFIC CORPORATION

SUCCESSOR TO WM. GAERTNER & CO.

ESTABLISHED 1896 INCORPORATED 1930

1201 WRIGHTWOOD AVENUE, CHICAGO

Our catalogs listing High Grade Scientific Instruments sent on request

The CENCO

Lecture Table Rotator

Another Cenco Convenience with Every Desirable Feature Included

Special Features

1. All speeds from zero to maximum in both directions, in infinitesimal steps.
2. The speed is adjustable while the motor is running.
3. The spindle rotates in ball bearings.
4. The friction disk has excellent wearing properties and great traction.
5. The friction drive plate may be clamped out of contact with the friction disk when the rotator is not in use.
6. The spindle of the rotator may be clamped in any position throughout 360°.
7. A stable tripod base with adjustable vertical supports renders the experiments visible to the entire class.
8. The motor is rated at 1/20 h.p., and this power is transmitted with very little loss to the spindle.
9. The rotator runs quietly.
10. A grooved pulley for round belt is furnished with the rotator.

No. 71620 (Shown in Use.)

Dimensions are as follows: Height over all above table, adjustable from 45 to 60 cm; table space occupied, 37x37 cm; power of motor, 1/20 h.p.; speed of motor, 1725 r. p. m.; diameter of pulley furnished, about 4.5 cm.

Complete as described, with socket, pulley and spindle with lock-nut for usual rotator accessories.

No.	A	B	C	D
	A. C.		D. C.	
For volts	110	220	110	220
Each	$100.00	$102.00	$100.00	$102.00

How to Order: *Cenco Lecture Table Rotator with friction drive, 1/20 h. p. motor, speed counter, ball-bearing spindle adjustable throughout 360°, mounted on support adjustable from 45 to 60 cm above table.*

CENTRAL SCIENTIFIC COMPANY

LABORATORY APPARATUS AND SUPPLIES

Apparatus and Chemicals

460-480 E. Ohio St. Chicago U.S.A.

The George Banta Publishing Company, Menasha, Wisconsin